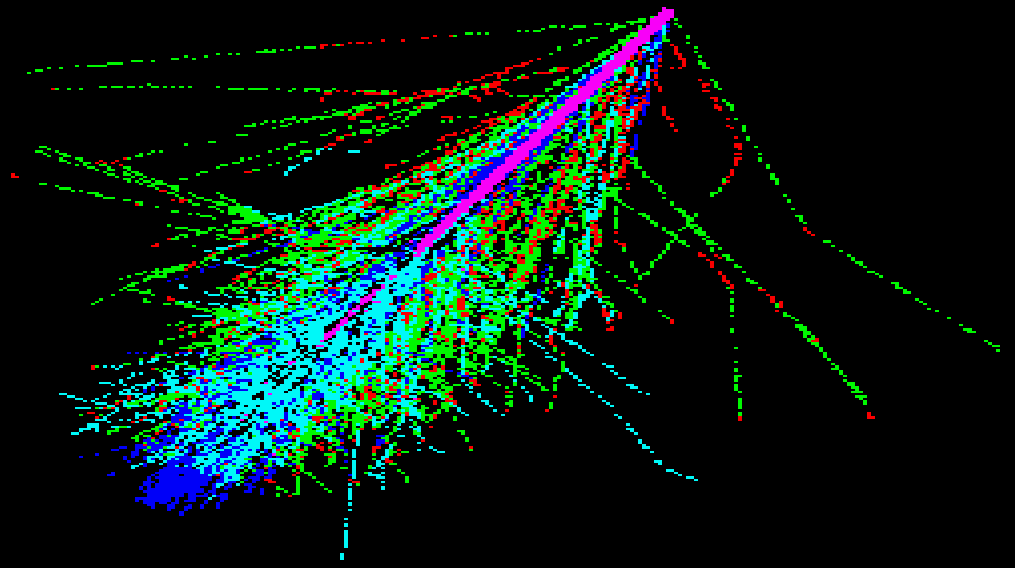
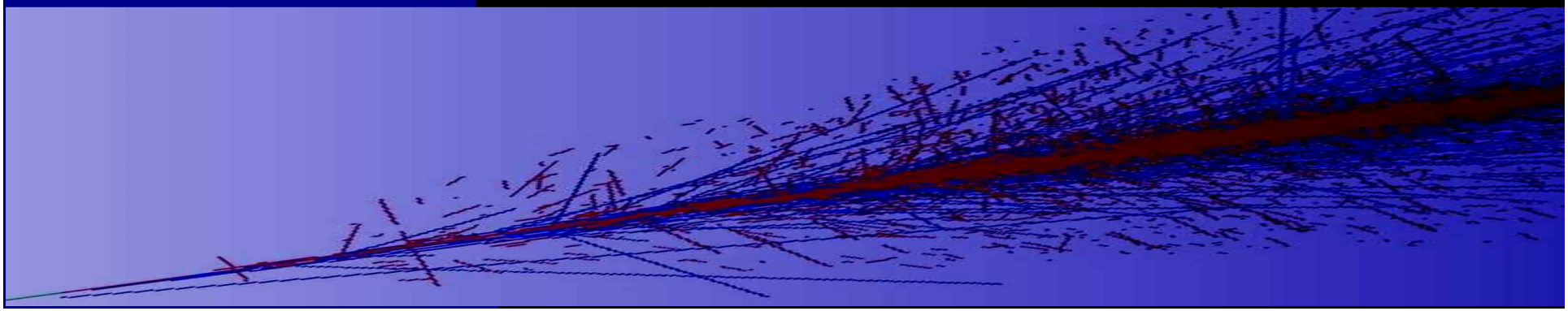
Latest results from the Pierre Auger Observatory



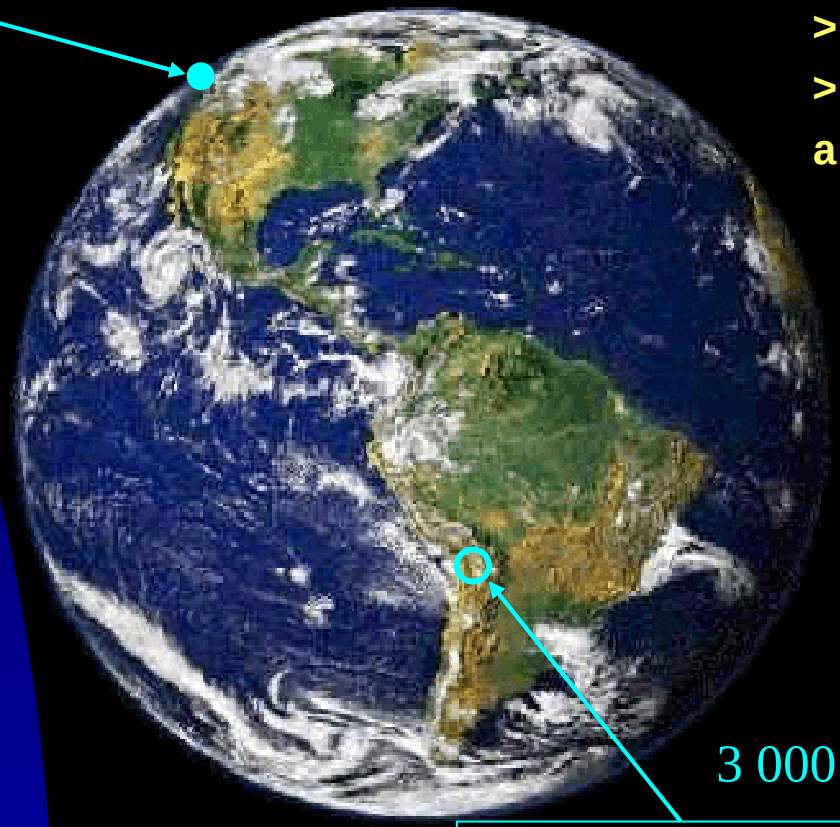
Angela V. Olinto

APC Paris Diderot

The University of Chicago



The Pierre Auger Observatory of Ultra-High Energy Cosmic Rays



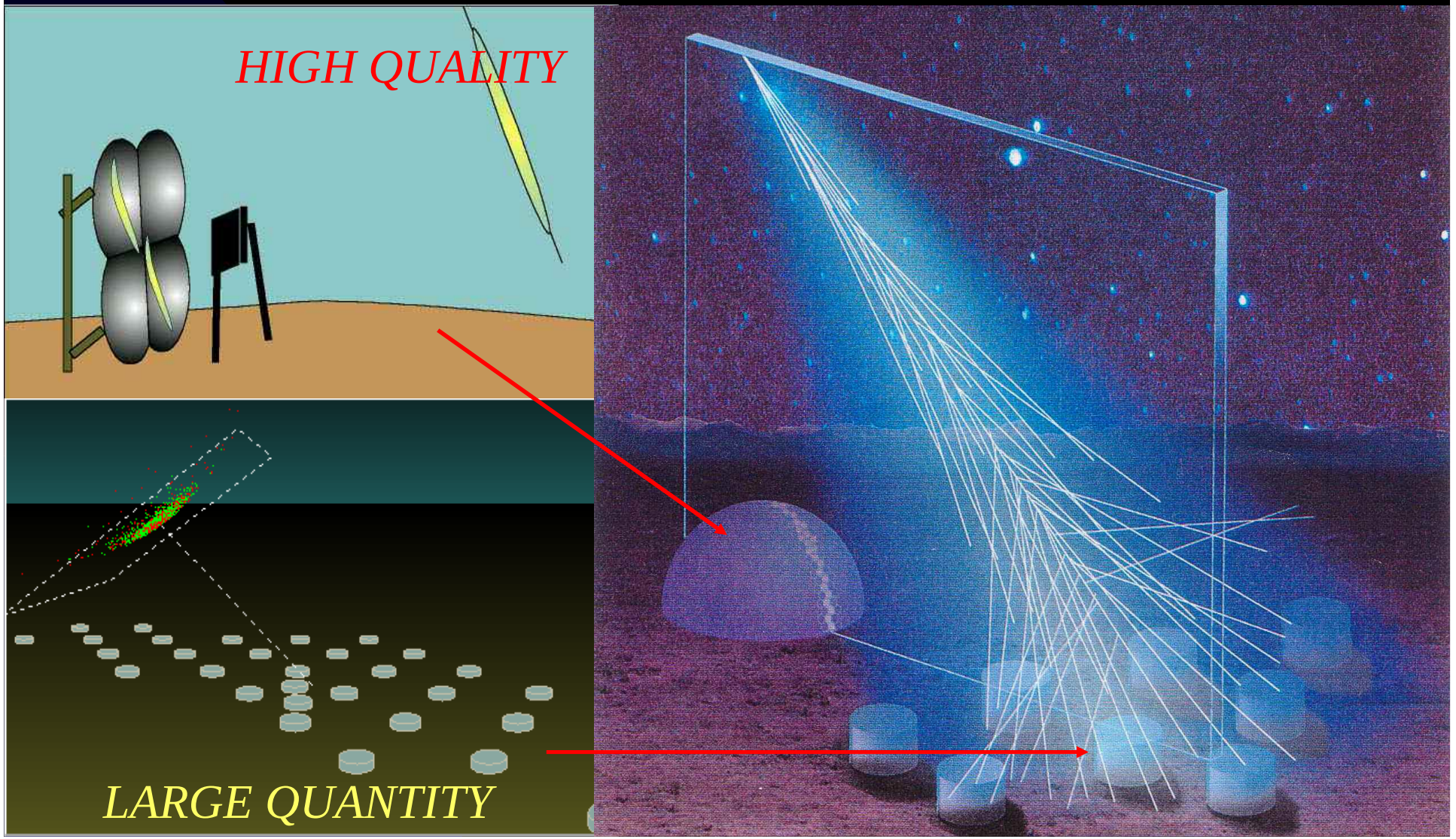
> 300 PhD scientists f
> 70 Institutions
and 17 countries

Argentina
Australia
Brasil
Bolivia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
UK
USA
Vietnam*

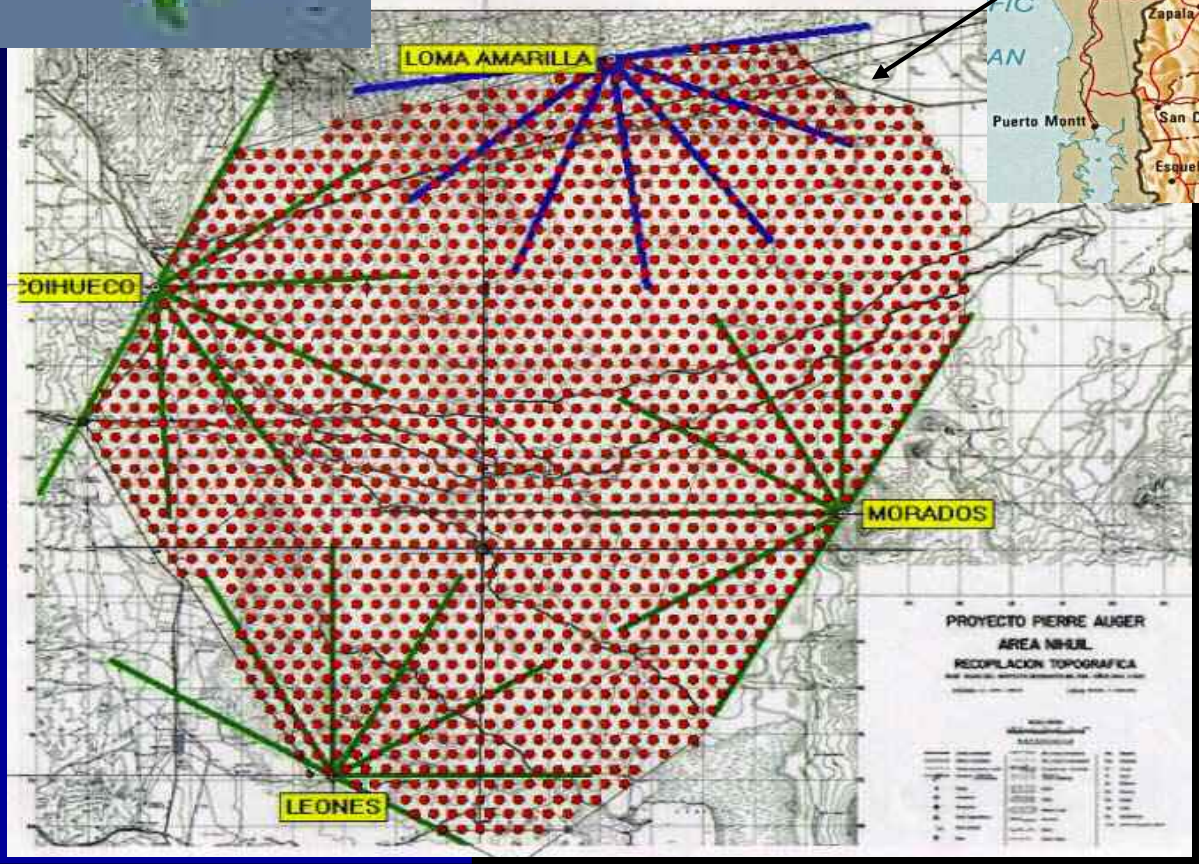
**Associate Countries*


PIERRE
AUGER
OBSERVATORY
Pierre Auger Colaboration Meeting
Malargüe, Argentina
March 15-19, 2006

The First Hybrid UHECR Observatory



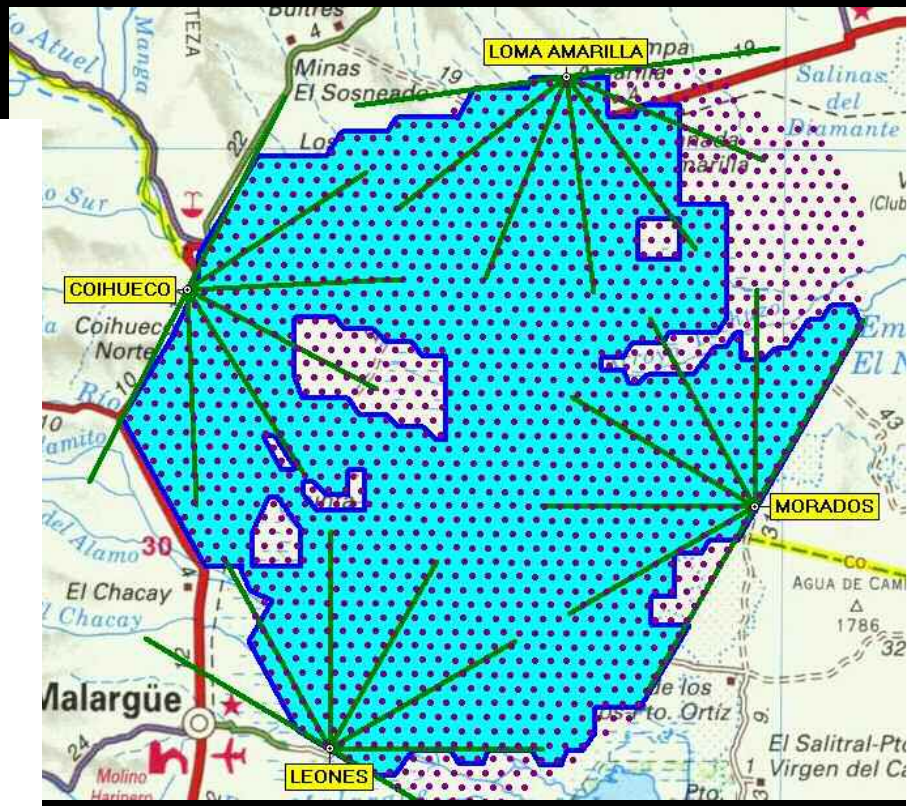
Auger South



1600 tanks in a 3,000 km² Surface Array
4 Fluorescence Detector Sites

The Surface Detector Array

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



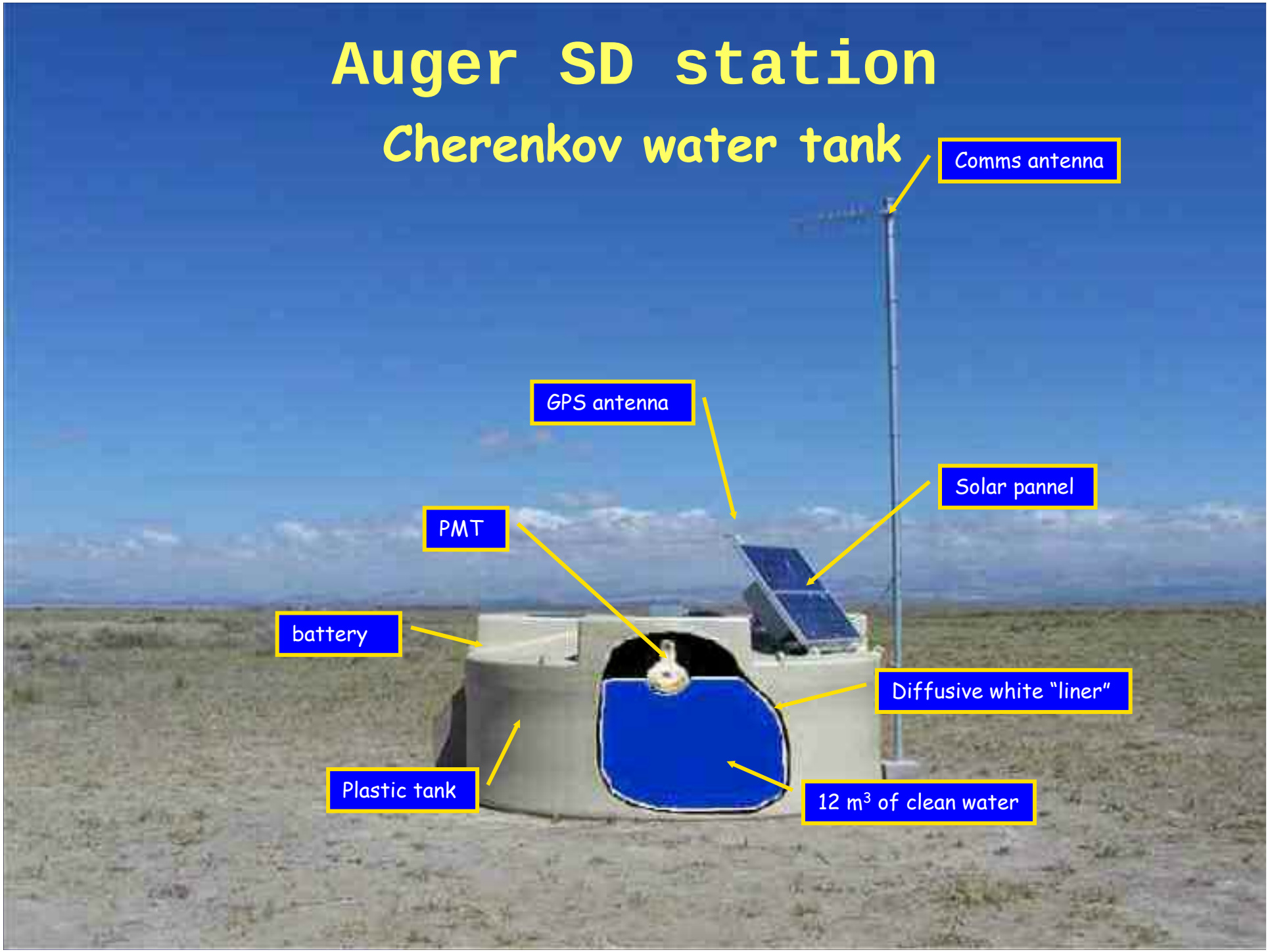
1482 deployed
1436 filled
1364 taking data
of the
1600 tanks, 3,000km²


1600 surface detectors

tanks aligned seen from Los Leones

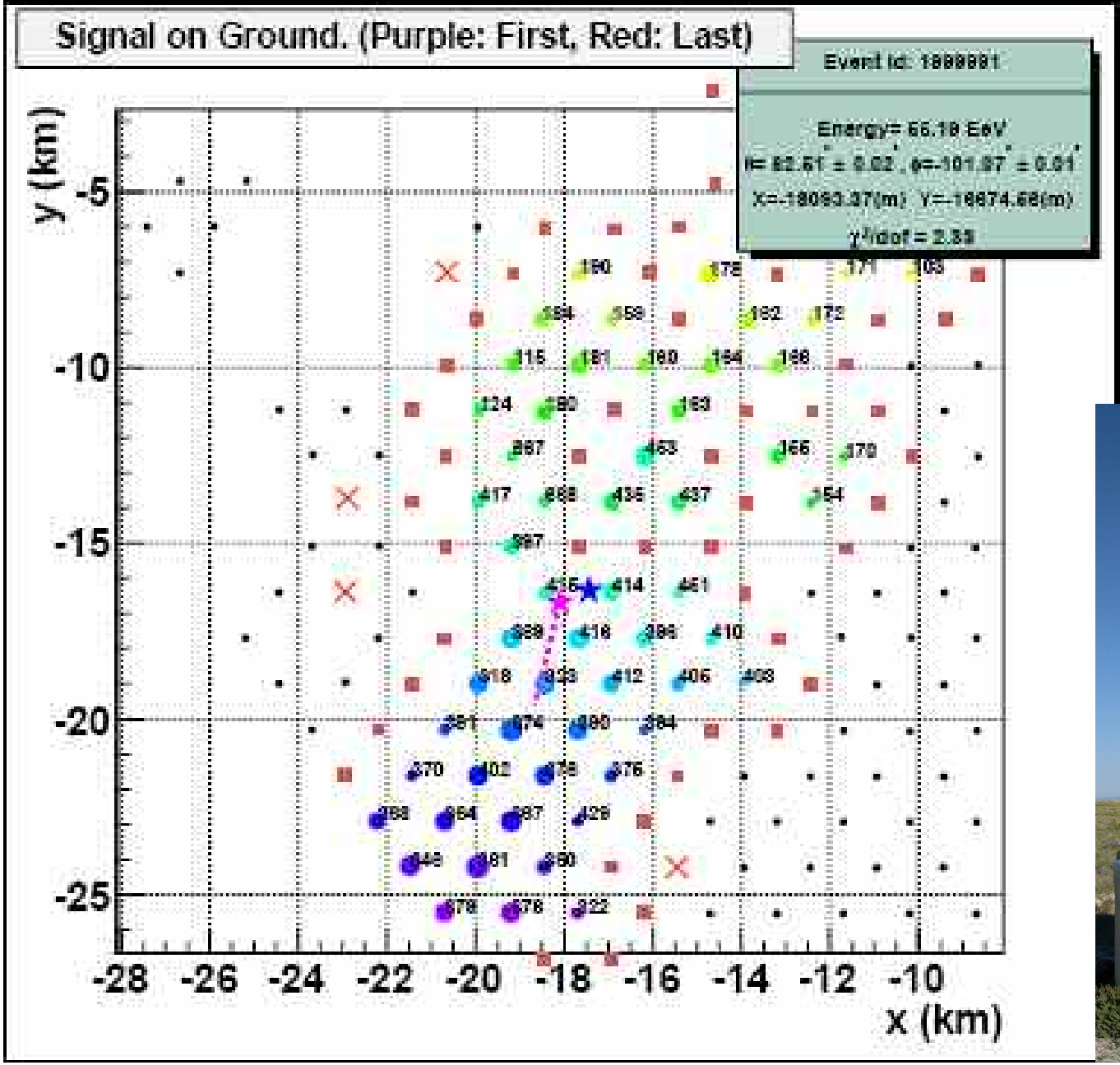
Auger SD station

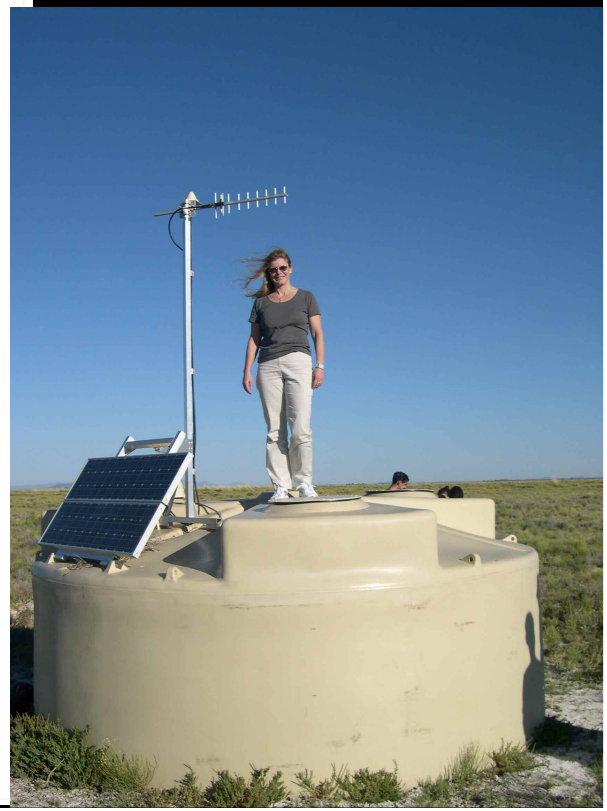
Cherenkov water tank



Event 1999991

Θ = 83
ϕ = -102
E = 55.2
R= 22 km
χ/dof =2.3
NTanks = 61

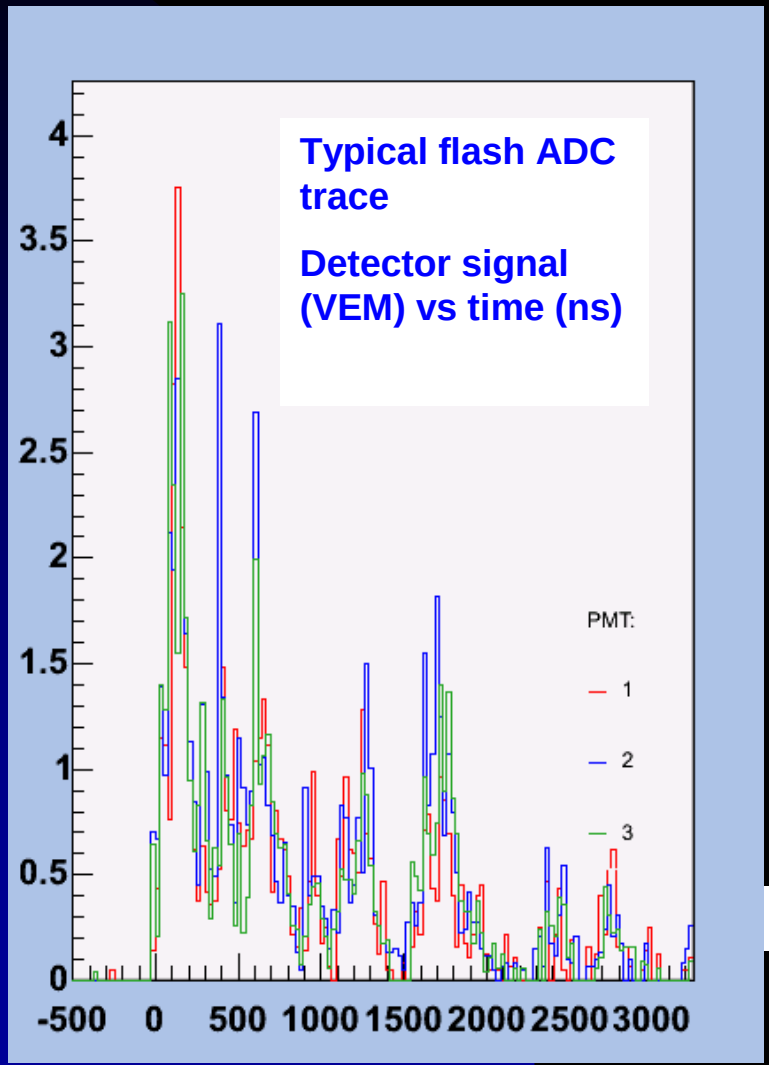


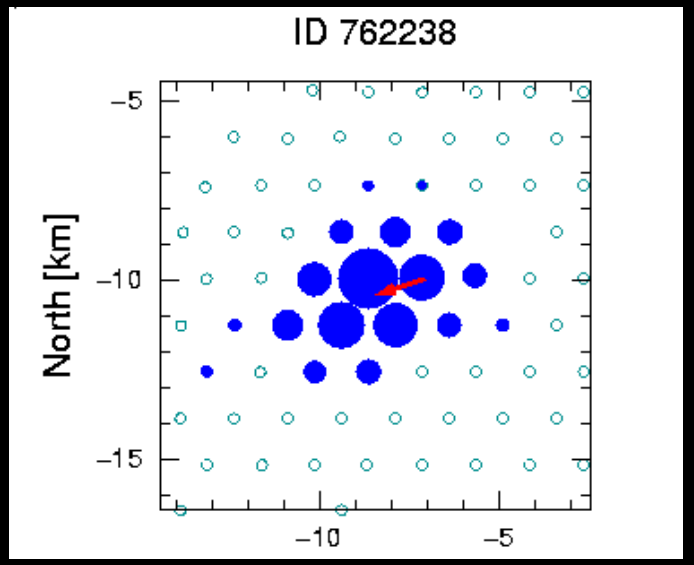


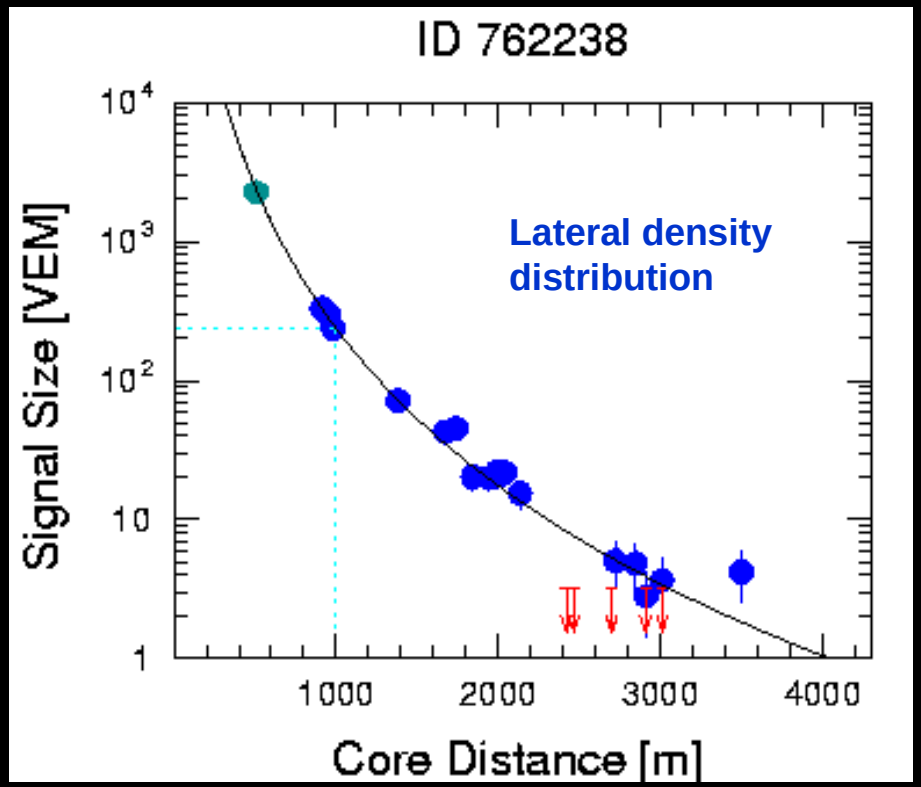
Example Event 1

A moderate angle event 762238

Zenith angle ~ 48º, Energy ~ 70 EeV



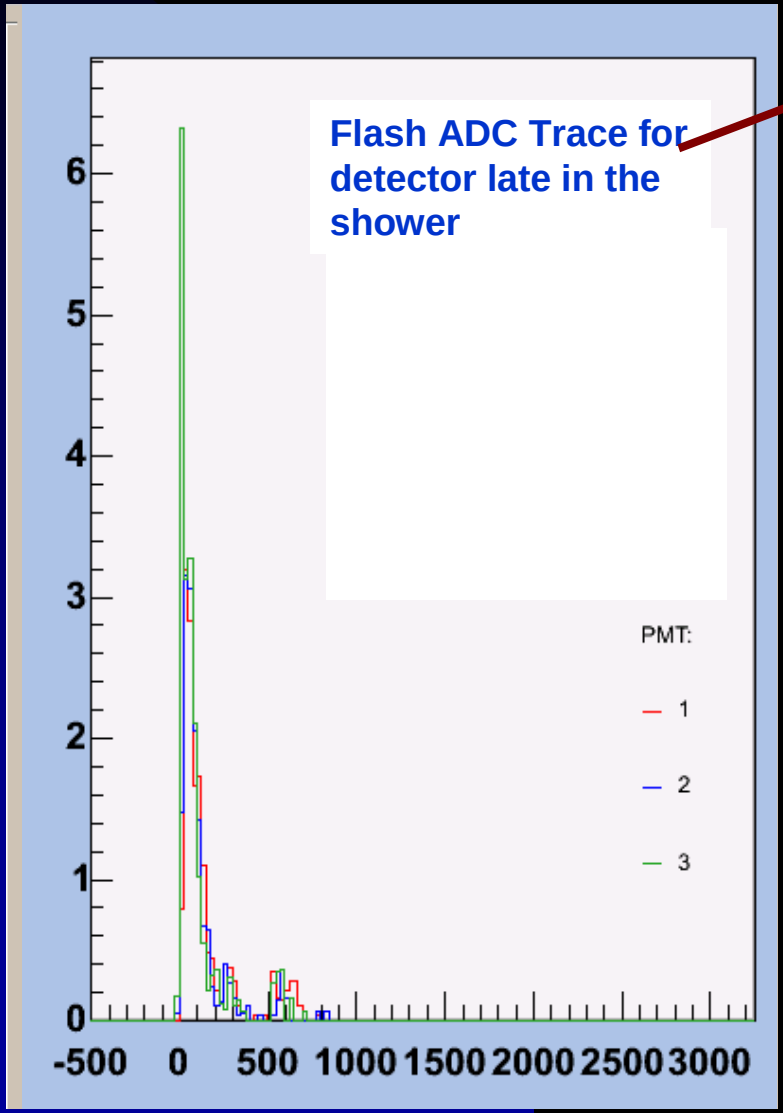


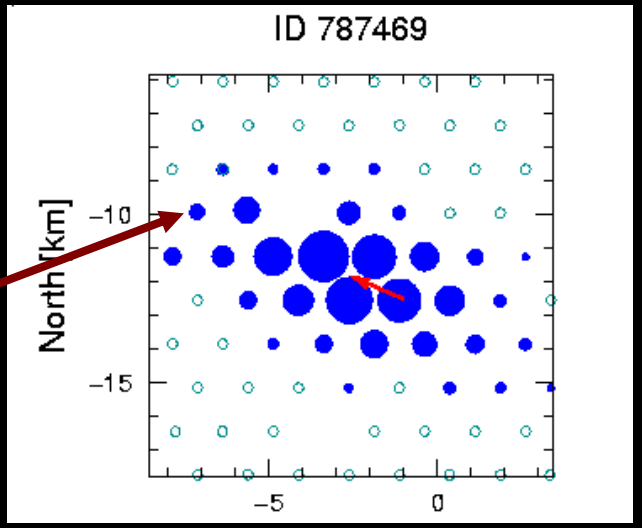


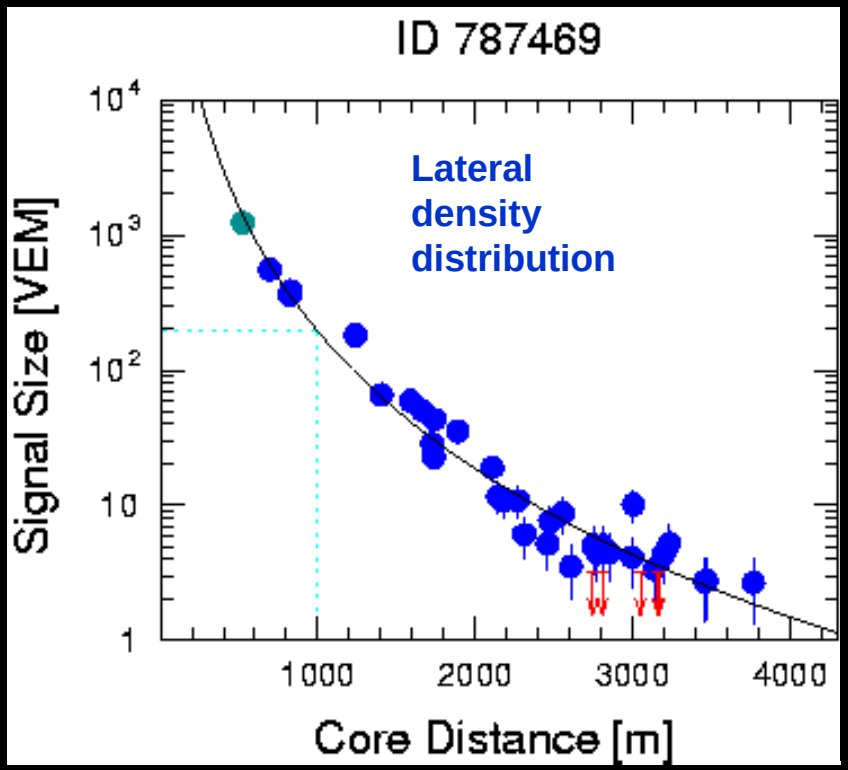
Example Event 2

A high zenith angle event - 787469

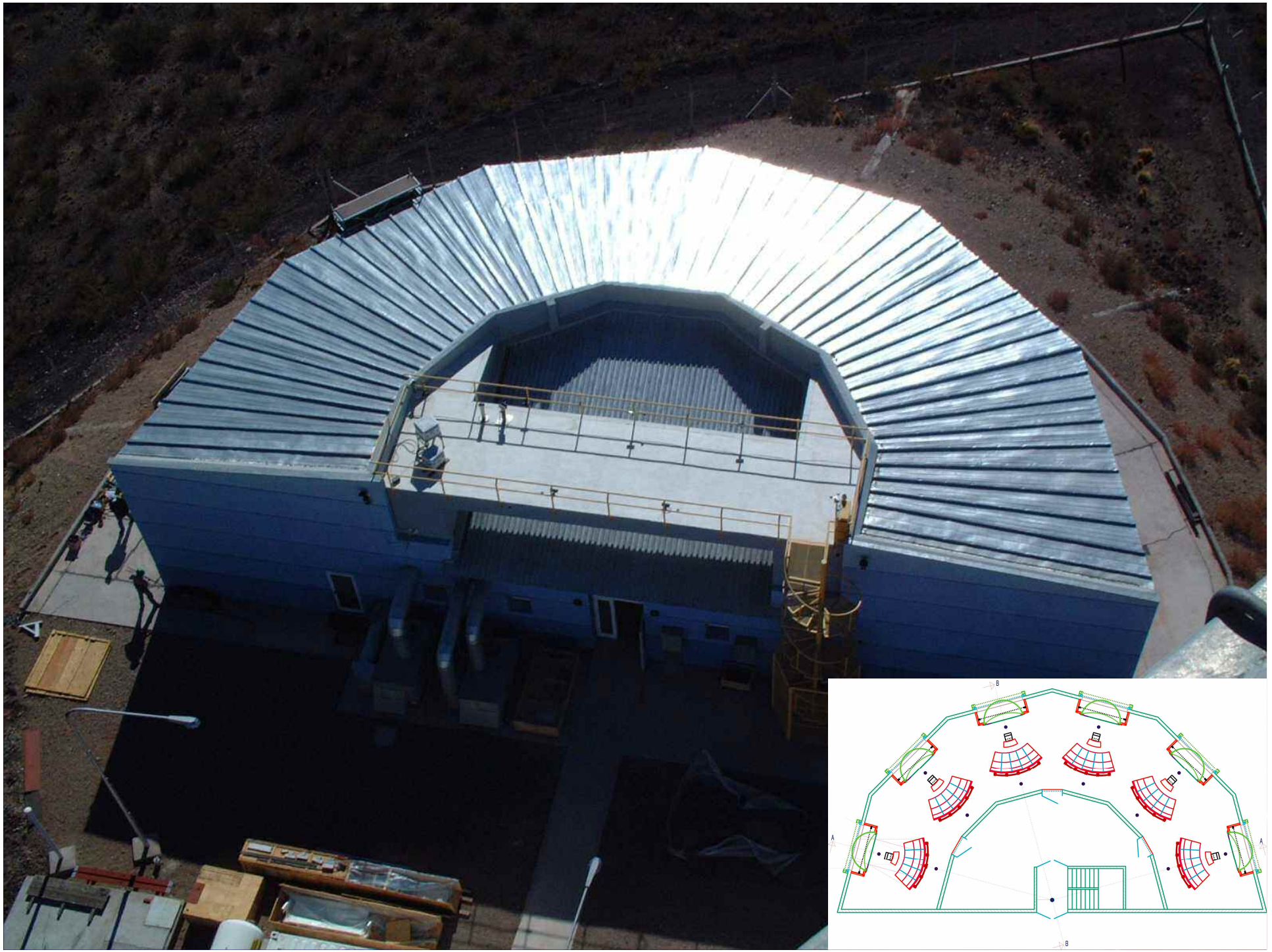
Zenith angle ~ 60º, Energy ~ 86 EeV

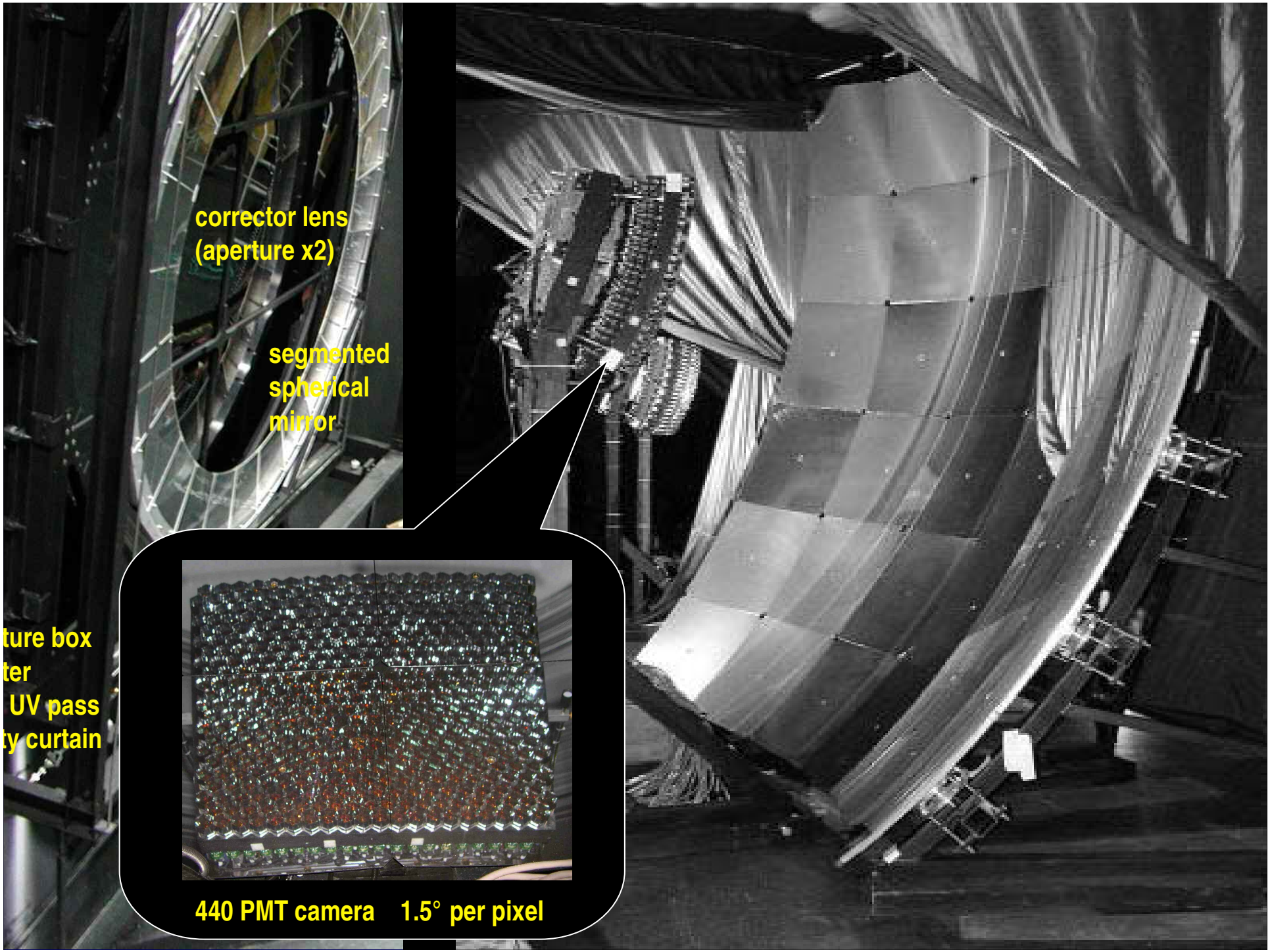




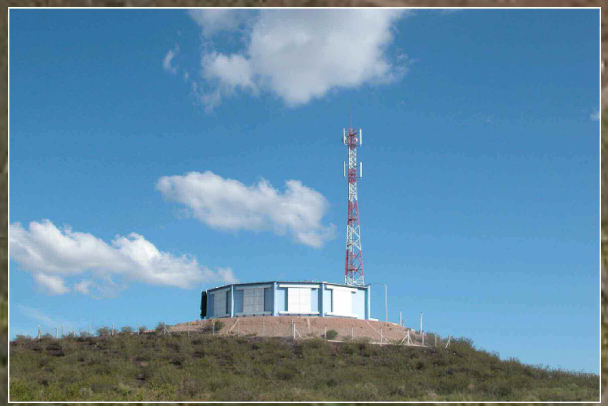


view of Los Leones Fluorescence

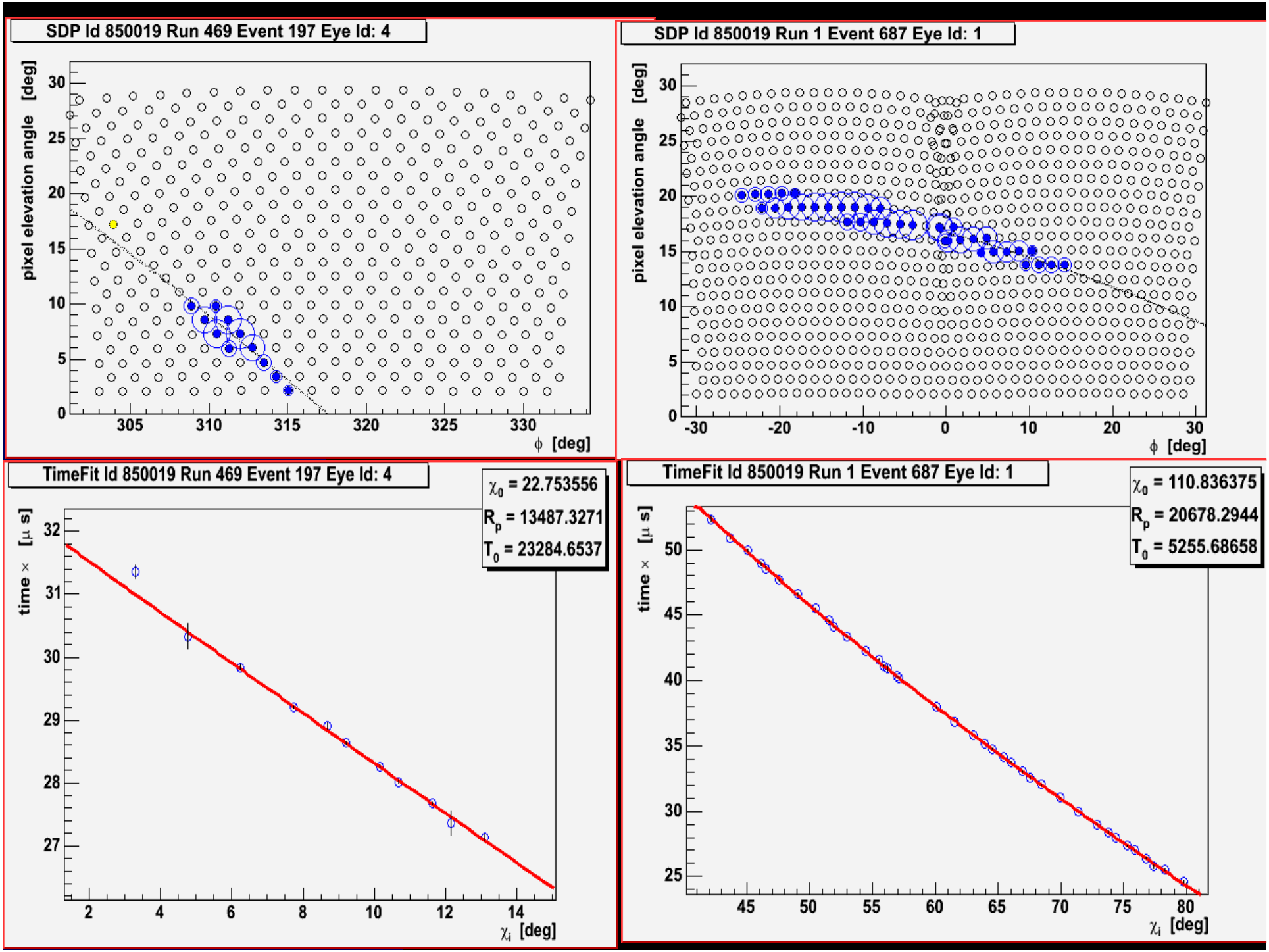


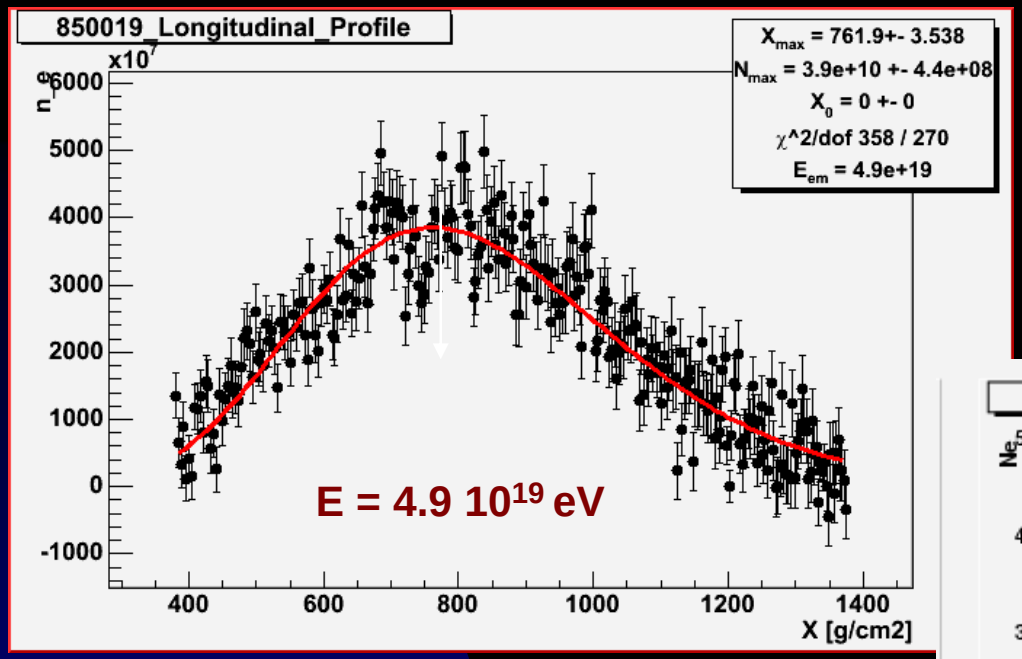

corrector lens
(aperture x2)
segmented
spherical
mirror
ture box
ter
UV pass
y curtain
440 PMT camera 1.5° per pixel

4 times 6 telescopes overlooking the site

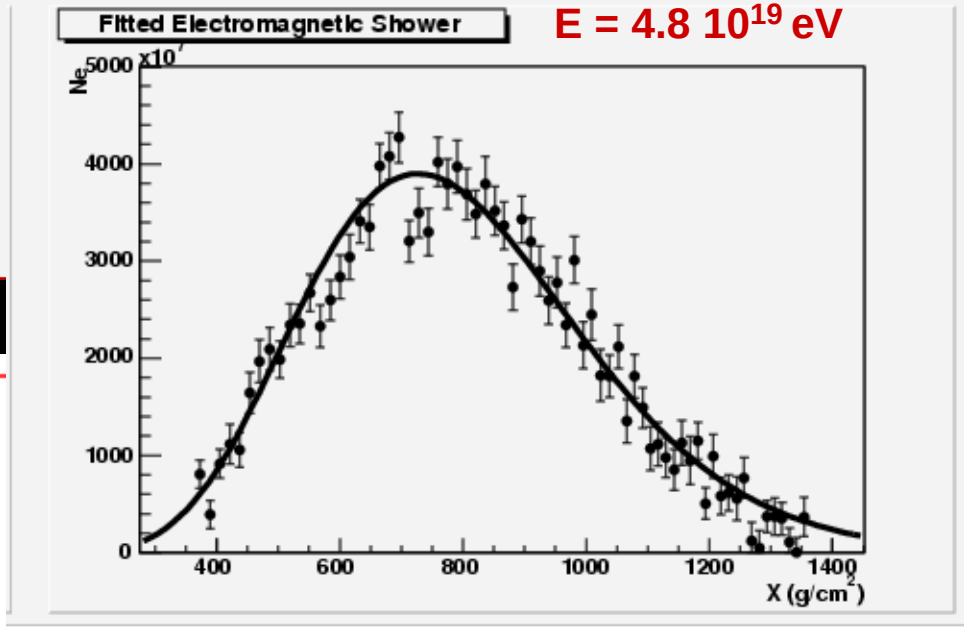


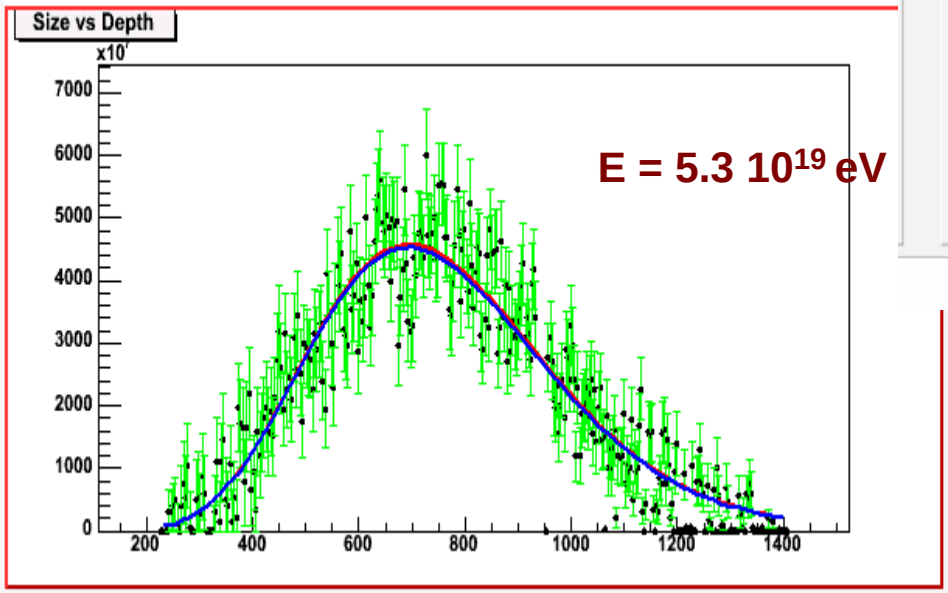
Completed!


SDP Id 850019 Run 469 Event 197 Eye Id: 4
pixel elevation angle [deg]
ϕ [deg]
SDP Id 850019 Run 1 Event 687 Eye Id: 1
pixel elevation angle [deg]
ϕ [deg]
TimeFit Id 850019 Run 469 Event 197 Eye Id: 4
χ0 = 22.753556
Rp = 13487.3271
T0 = 23284.6537
time × [μ s]
χi [deg]
TimeFit Id 850019 Run 1 Event 687 Eye Id: 1
χ0 = 110.836375
Rp = 20678.2944
T0 = 5255.68658
time × [μ s]
χi [deg]



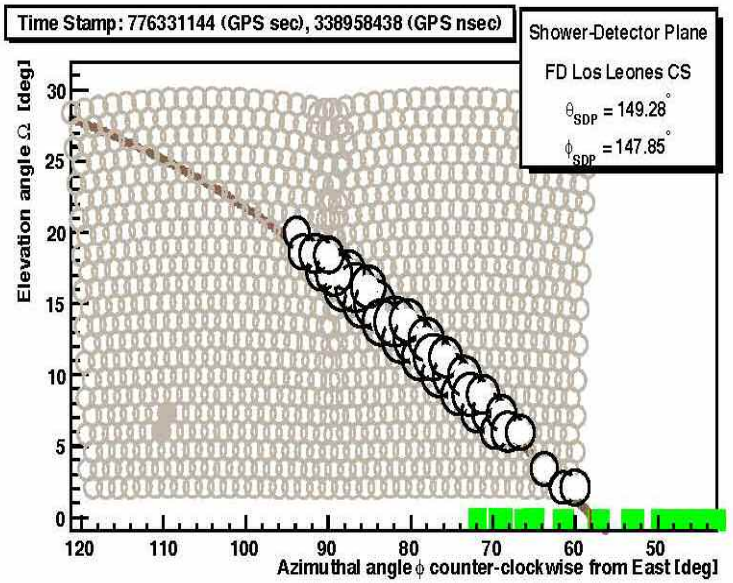
Independent analyses of stereo events

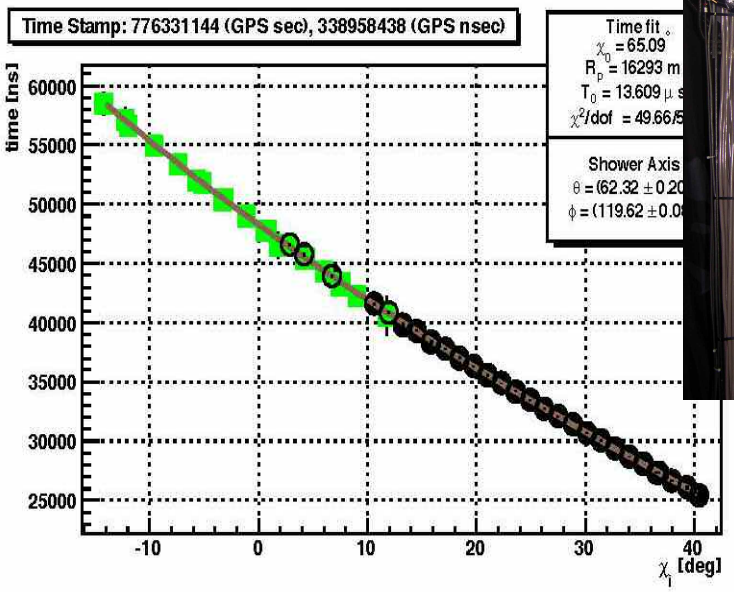


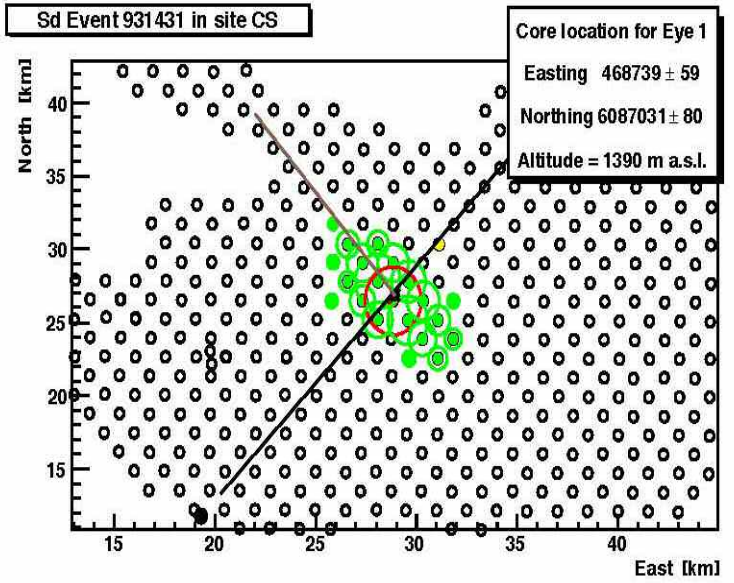


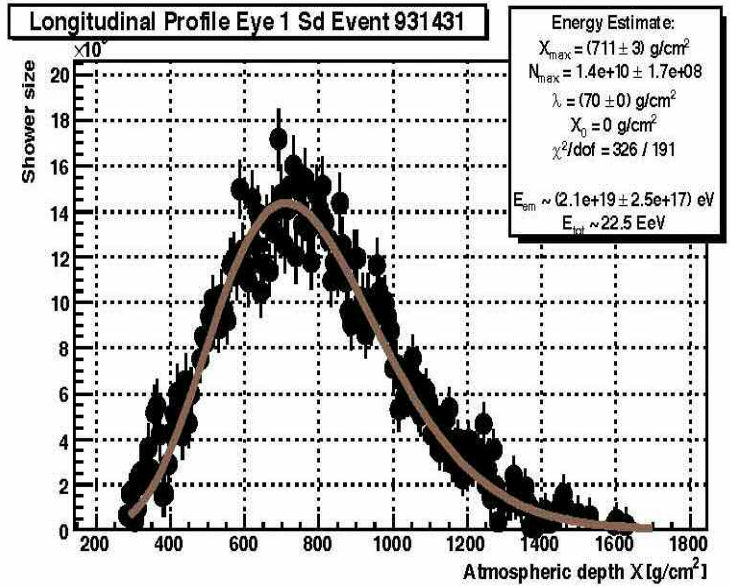
E_{em} calculated by fitting a GH profile and integrating

A Hybrid Event



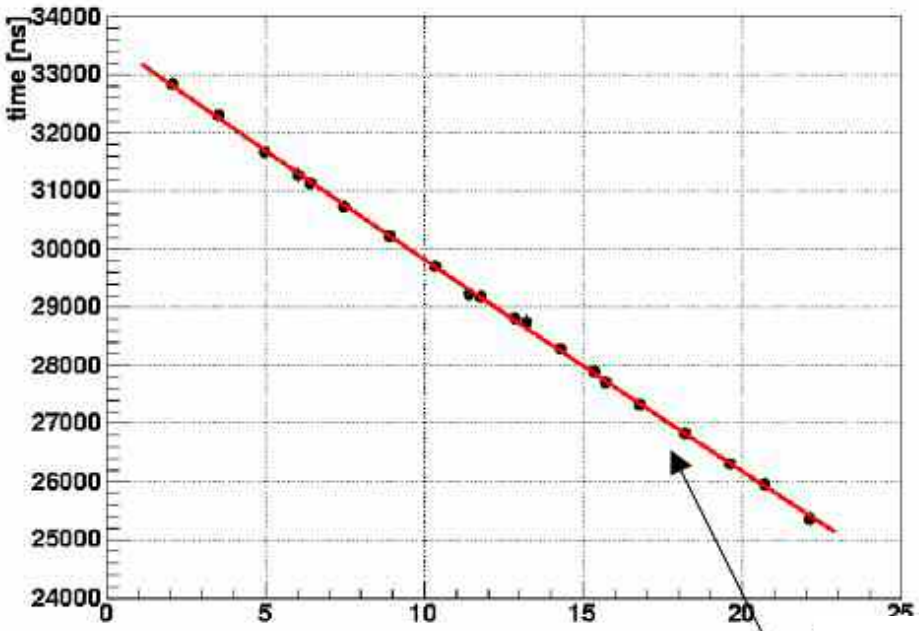


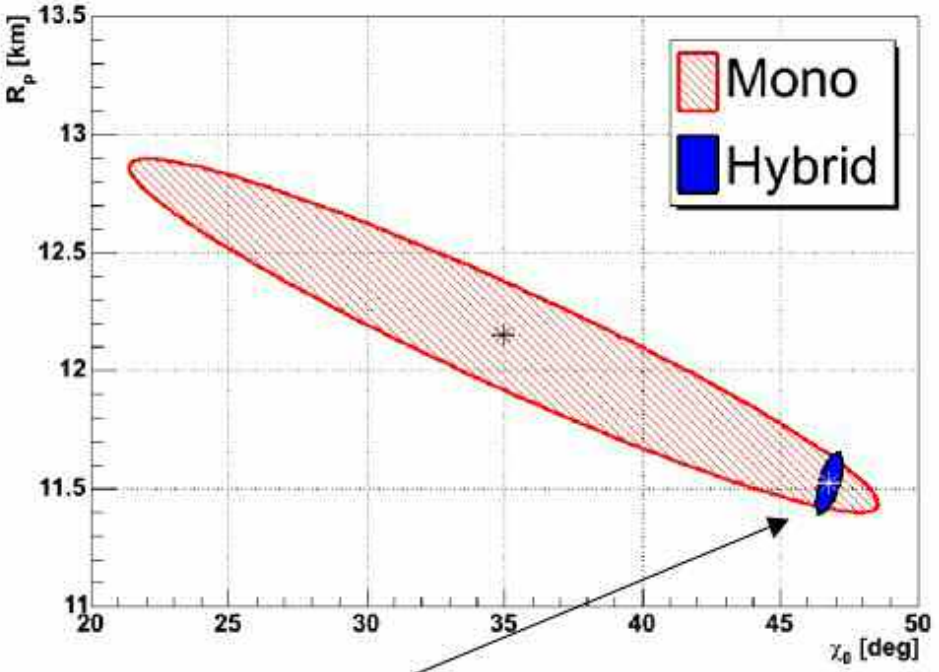




Time, t

R_p km





X°

≈ line but

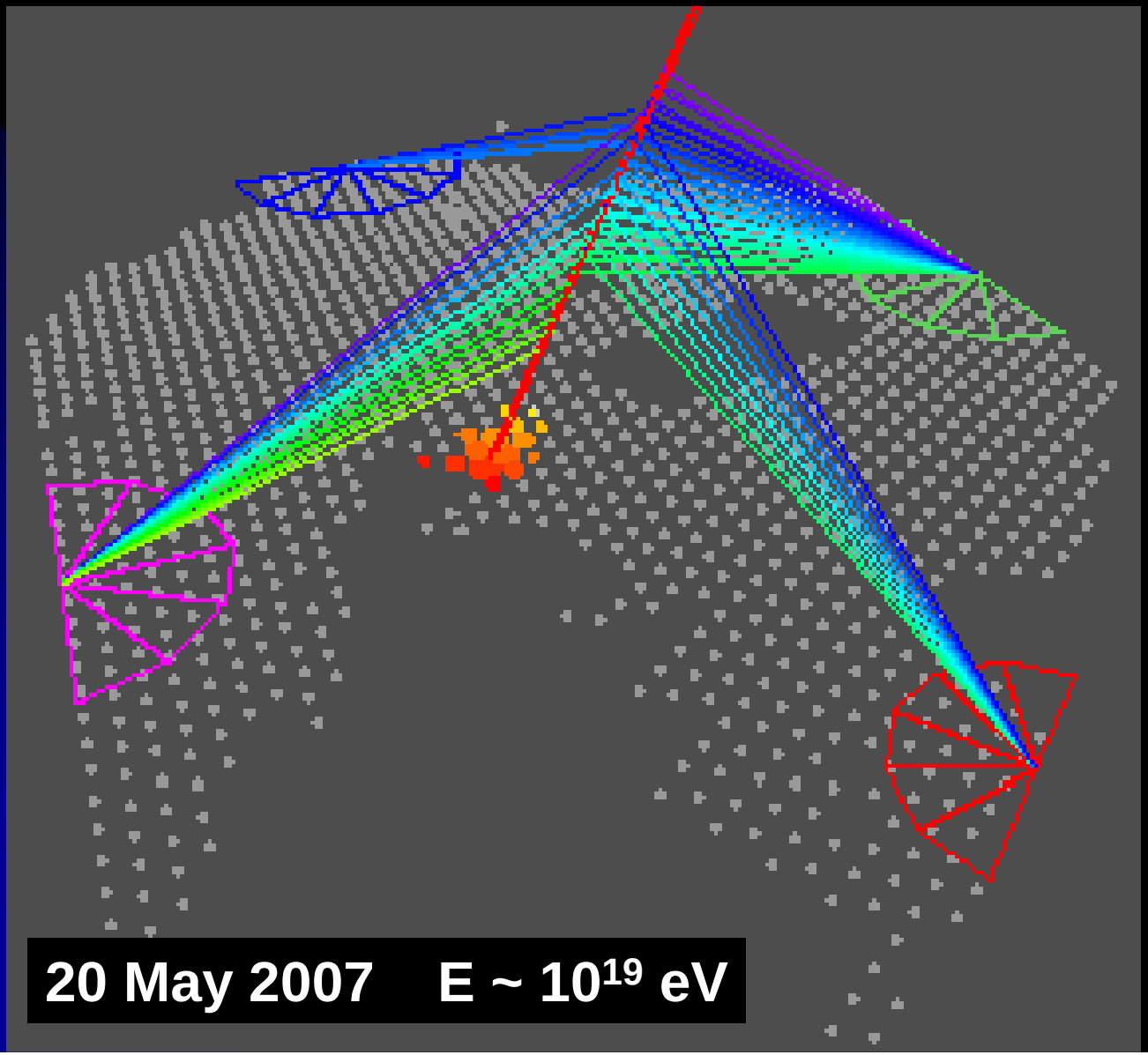
3 free parameters

T_0 from tank!

$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$

Watson ICRC07

1st - 4 Fold Hybrid Event



Hybrid Era

	HYBRID	SD only	FD only
Energy	A & M indep	depend	independ
Aperture	E, A, M indep	independ	depend
Angular Resolution	~ 0.2^{o}	~1-2^{o}	~3-5^{o}

E= energy, A= mass, M = hadronic model

Goals of the Auger Observatory

*** Determine the Origin of UHECRs ***

Energy Spectrum

Composition

Arrival Direction Distribution

Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

features? ankle, GZK; injection? Propagation?

Composition

protons, nuclei, photons, neutrinos

Arrival Direction Distribution

anisotropies?

Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

features? ankle, GZK; injection? Propagation?

Composition

protons, nuclei, photons, neutrinos

Arrival Direction Distribution

anisotropies?

Cosmic Ray Spectrum

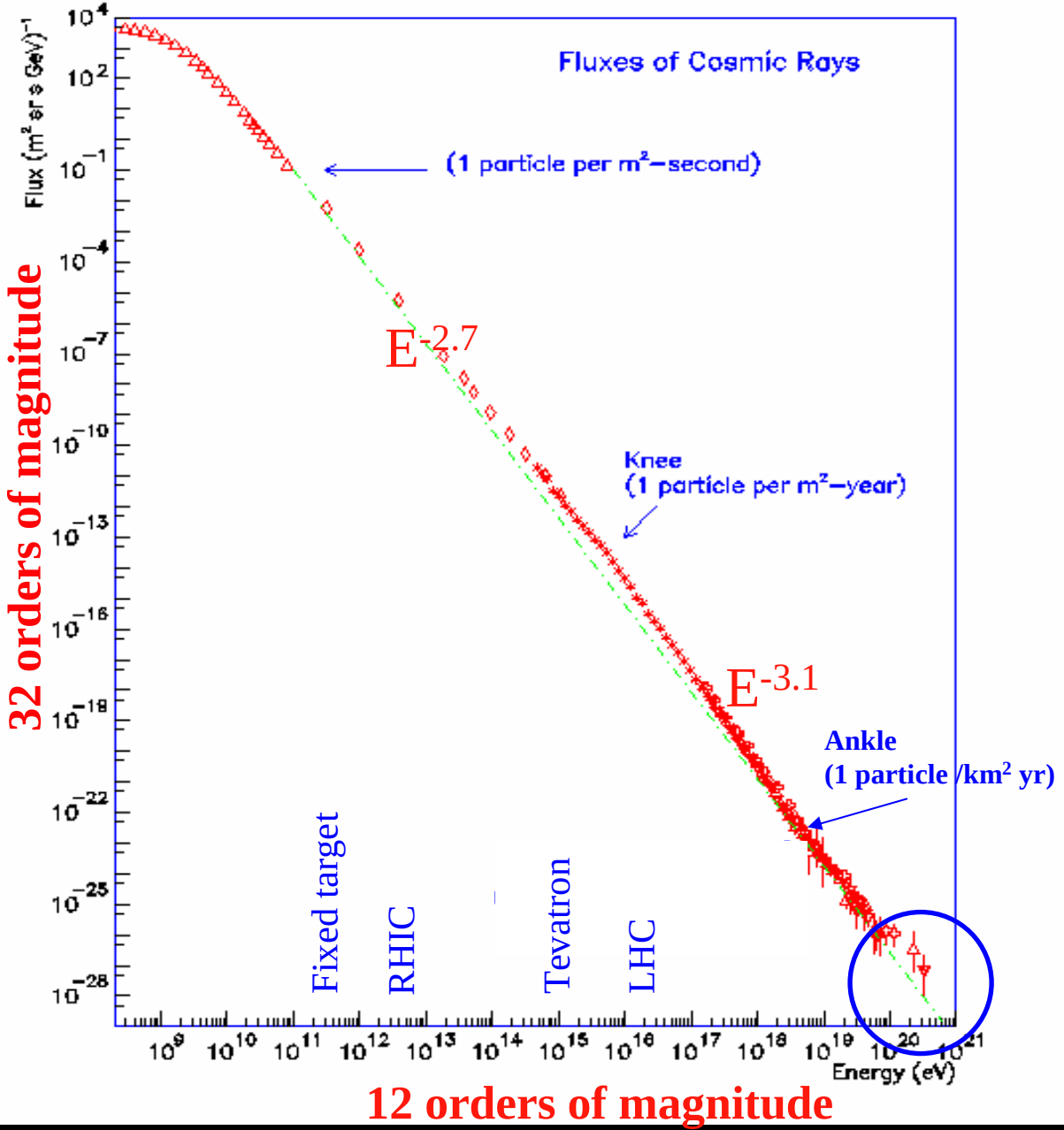
1912 discovered by Victor Hess

1938 Pierre Auger discovered Extensive Air Showers (EAS)

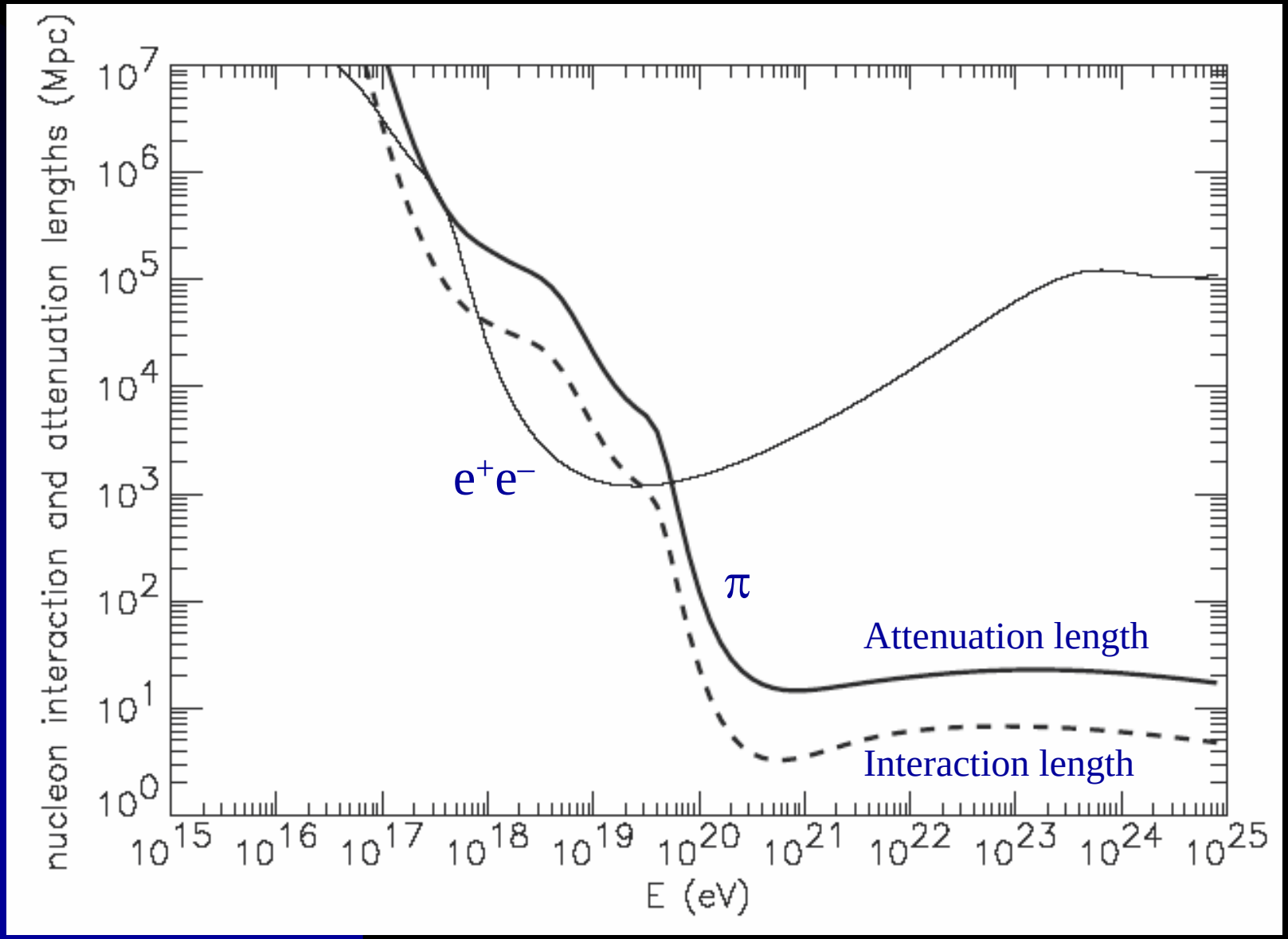
Energy range:

~ 10^9 eV to > 10^{20} eV

$E_{cm} = PeV\ (E_{uhecr}/ZeV)^{1/2}\ (2A)^{1/2}$

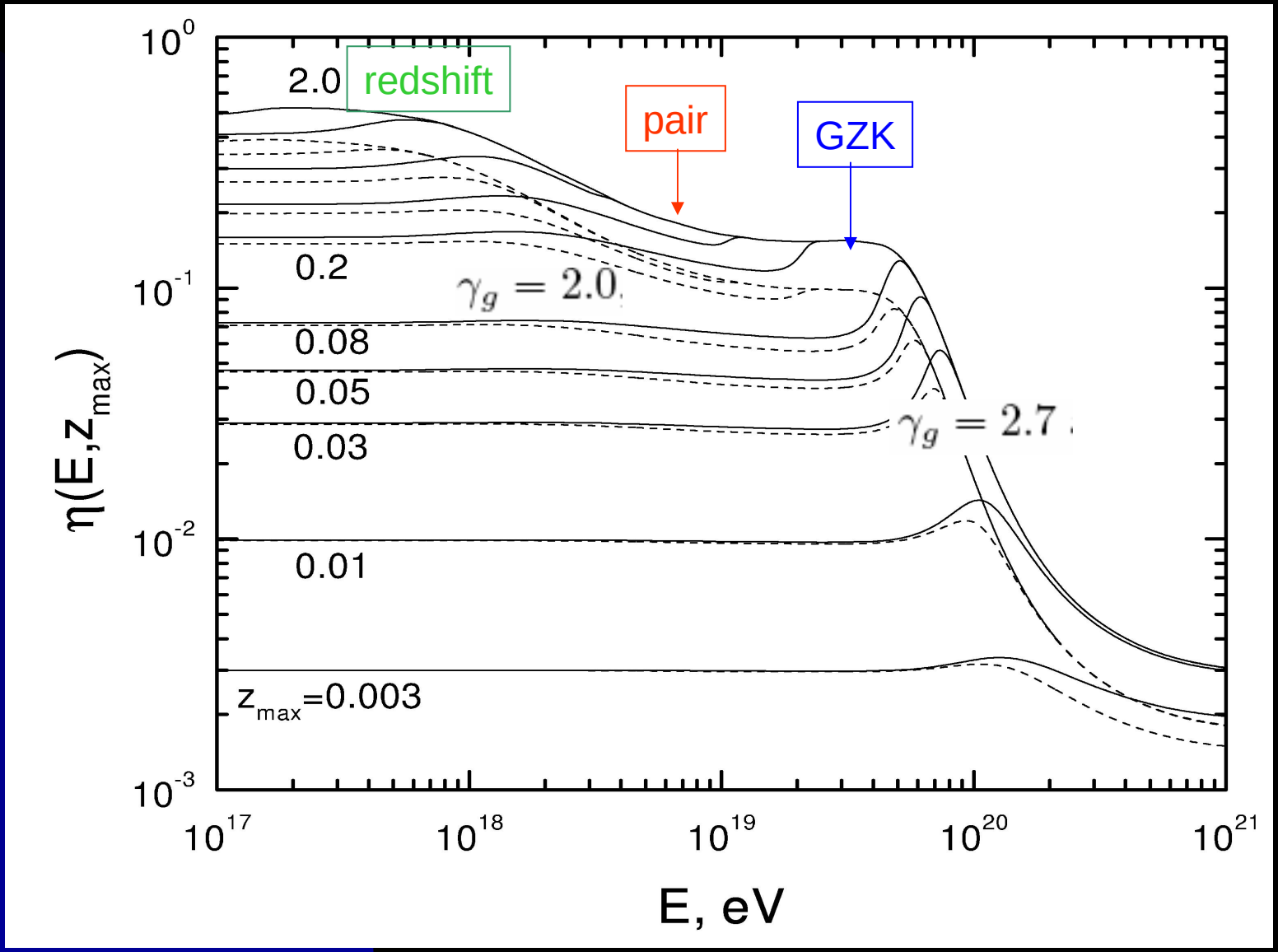


Attenuation length



Energy loss Features for protons

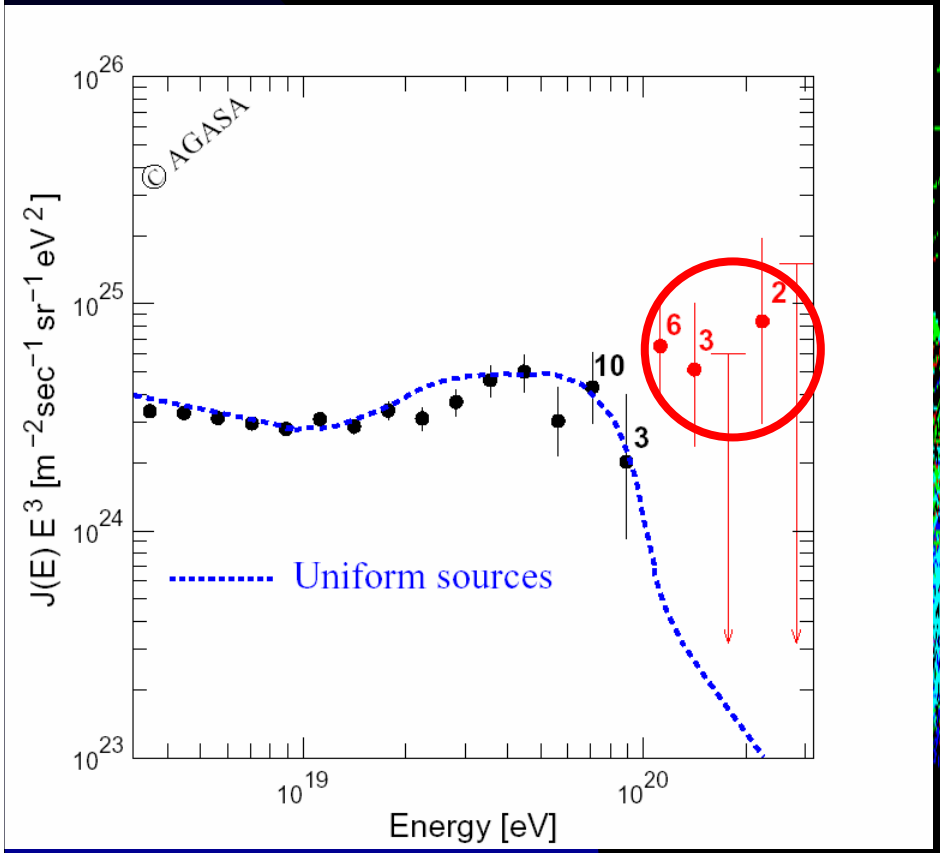
Berezinsky et al. 03

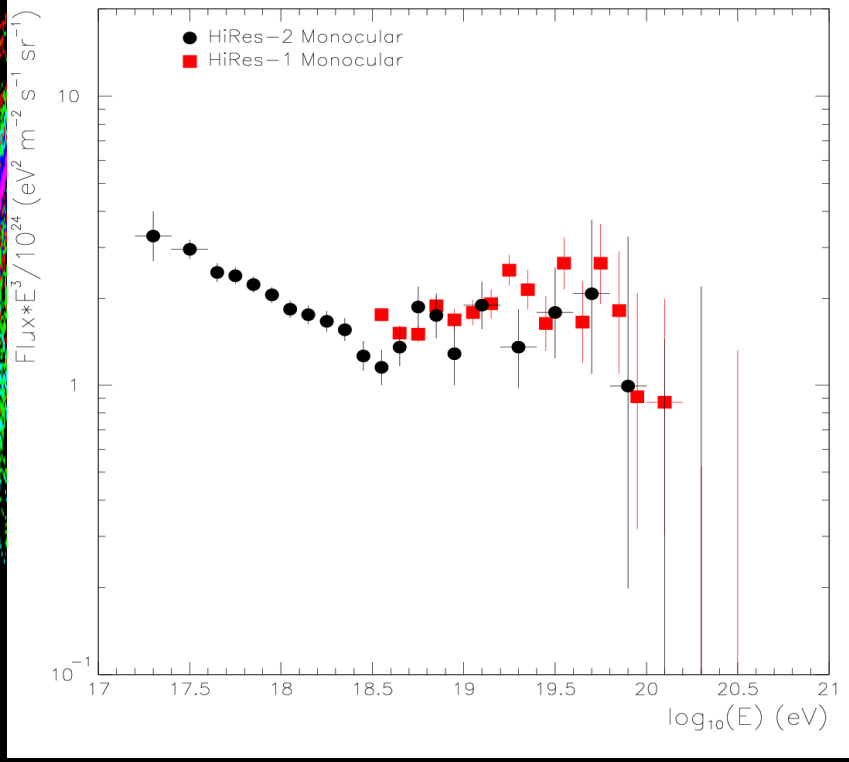


modification factor: $J_{obs}(E,z) = \eta(E,z) \times J_{injec}(E)$

AGASA

High Resolution Fly's Eye





No GZK cutoff

Consistent w/ GZK cutoff

Statistical Challenge

To reach > 10^4 - 10^5 km^2 sr yr

Past experiments ~ 10^3 km^2 sr yr

AGASA (100 km^2 array scintillators) 1984 - 2003

exposure ~ 1.6 10^3 km^2 sr yr

HiRes (Binocular Fluorescence Telescopes) 1997 - 2006

exposure ~ 4-6 10^3 km^2 sr yr

PIERRE AUGER Observatory (South)

3,000 km^2 array + 4 Fluorescence Telescopes

Aperture 6,600 km^2 sr - reach > 10^4 in 2 years

Energy Reconstruction

1. Determination of S(1000) =

   the signal 1000 m away from shower axis

2. Convertion into S_{38} = S(1000) that would have been measured at a 38° zenith angle

$$S_{38} = S_{1000}/(1 + ax + bx^2)$$

$$x = \cos^2\theta - \cos^2 38^\circ$$

$$a = 0.94 \pm 0.06$$

$$b = -1.21 \pm 0.27$$

3. Convertion into an FD-equivalent energy

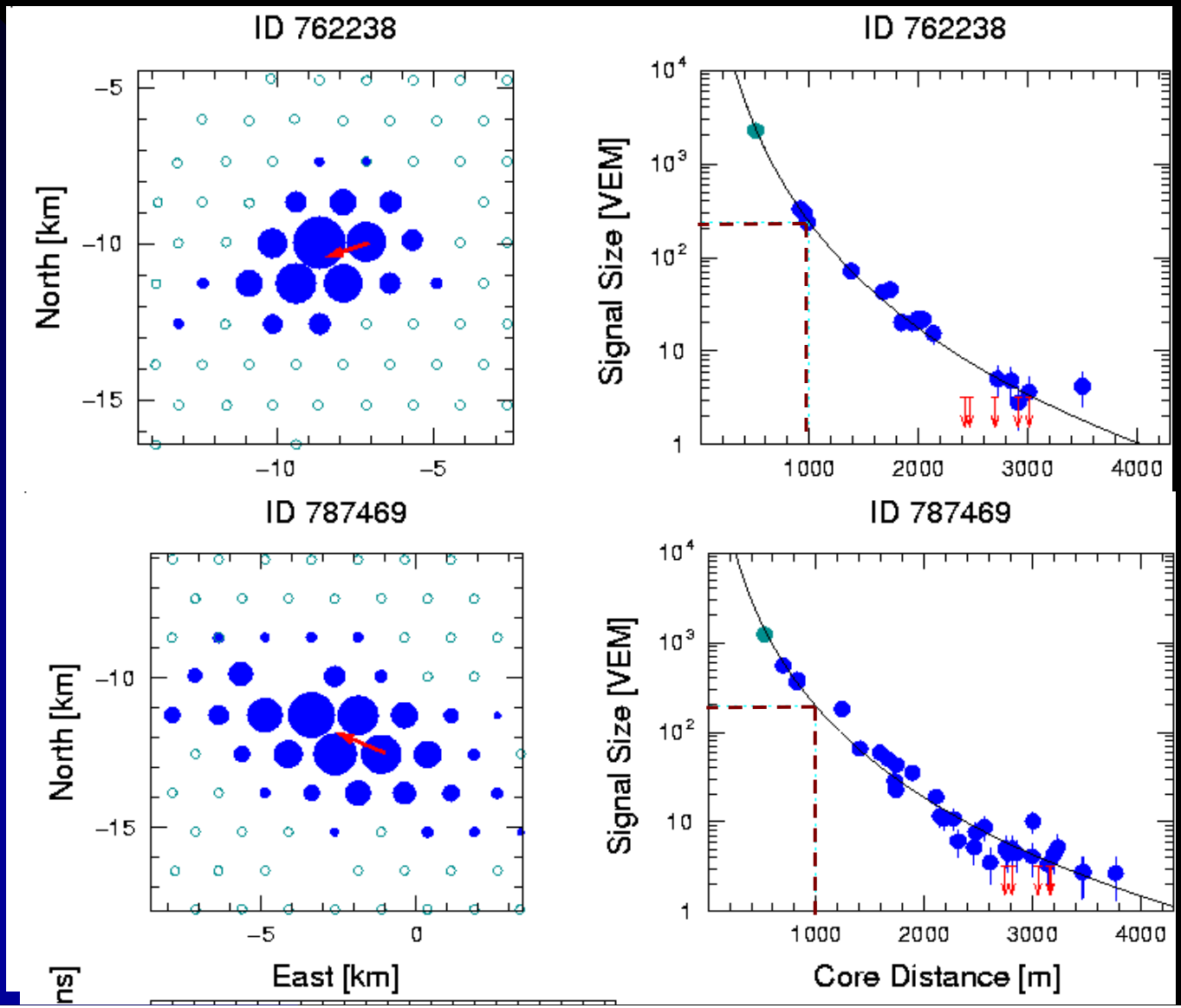
$$\log E_{FD} = A + B \log(S_{38})$$

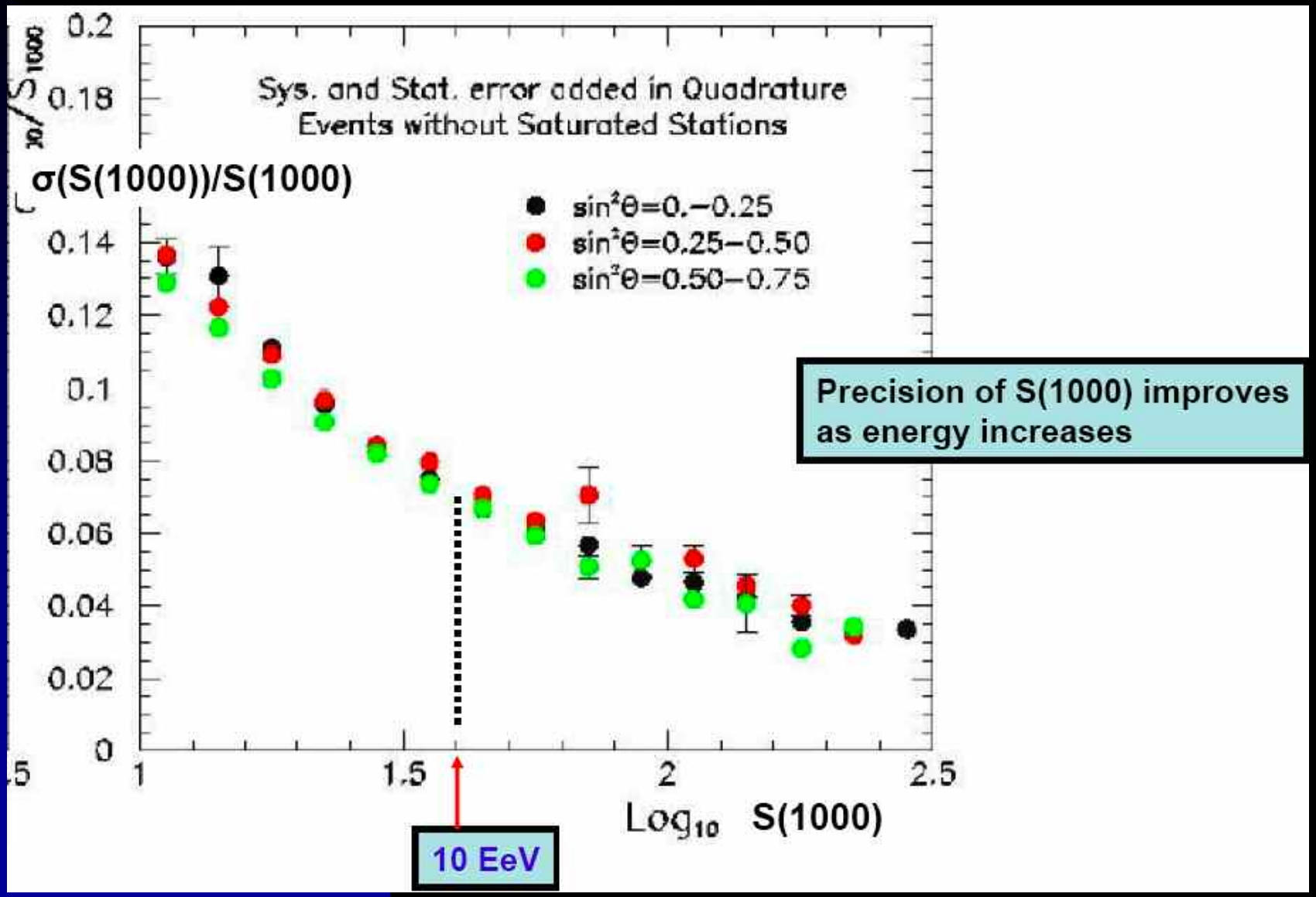
$$A = 17.08 \pm 0.03$$

$$B = 1.13 \pm 0.02$$

Energy Reconstruction S(1000)

SD energy estimator: interpolated signal in a tank at 1000 meters and 38°




Sys. and Stat. error added in Quadrature
Events without Saturated Stations
σ(S(1000))/S(1000)
sin²θ=0.–0.25
sin²θ=0.25–0.50
sin²θ=0.50–0.75
0.2
0.18
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
1.5
2
2.5
Log10 S(1000)
10 EeV
Precision of S(1000) improves as energy increases

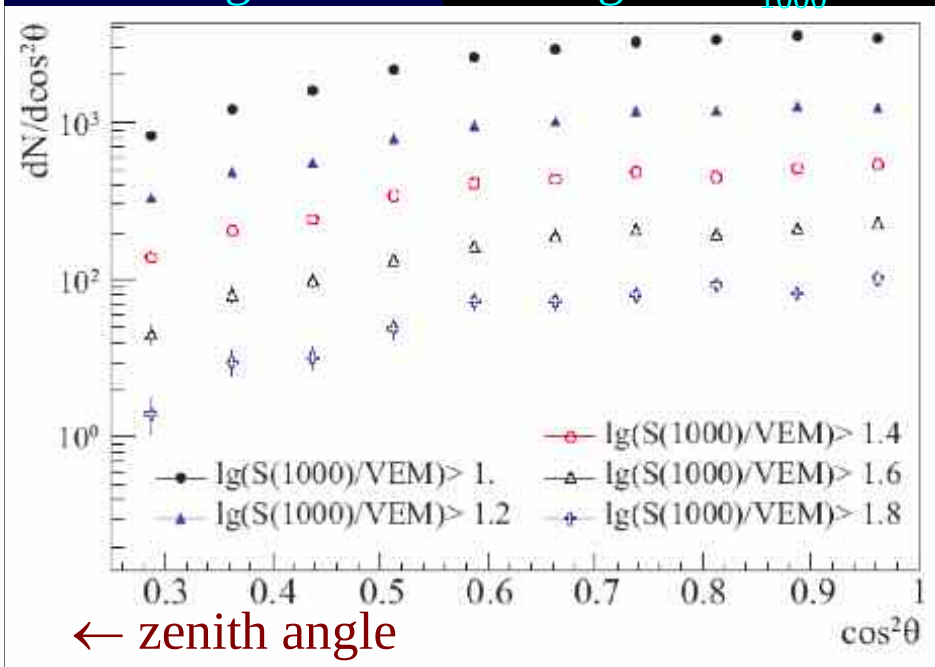
Constant Intensity Curve

equal flux ⇔ equal energy

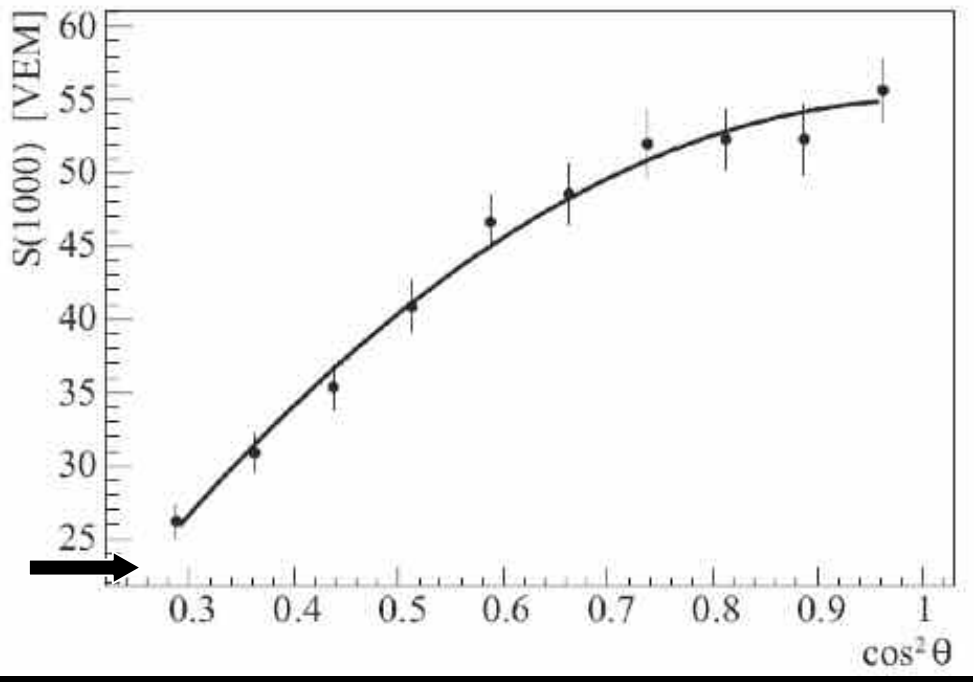
S_{1000}:
→ depends on energy & zenith angle

Constant Intensity Method
→ relate $S_{1000}(\theta)$ to the value of S_{1000} at a reference zenith angle, 38°: S_{38}

Integral flux above a given S_{1000}



← zenith angle

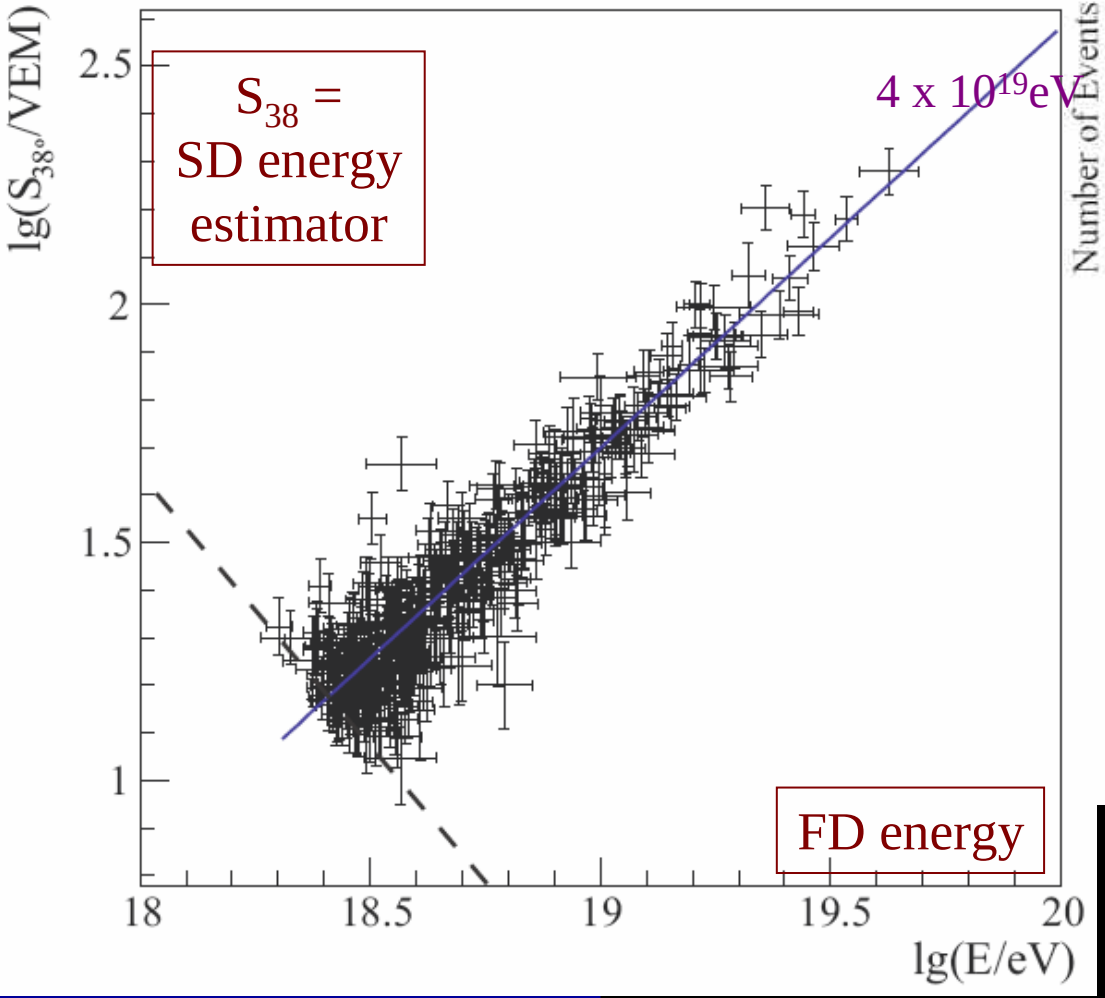


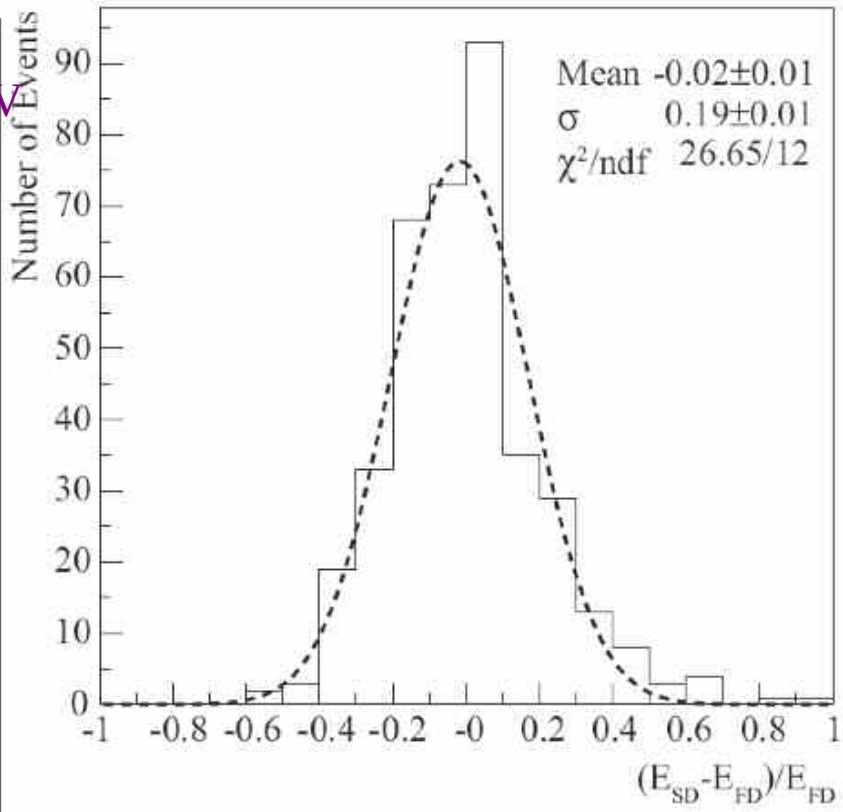
Attenuation curve: at a given energy, lower signal at larger zenith angle

Energy Calibration

387 hybrid events

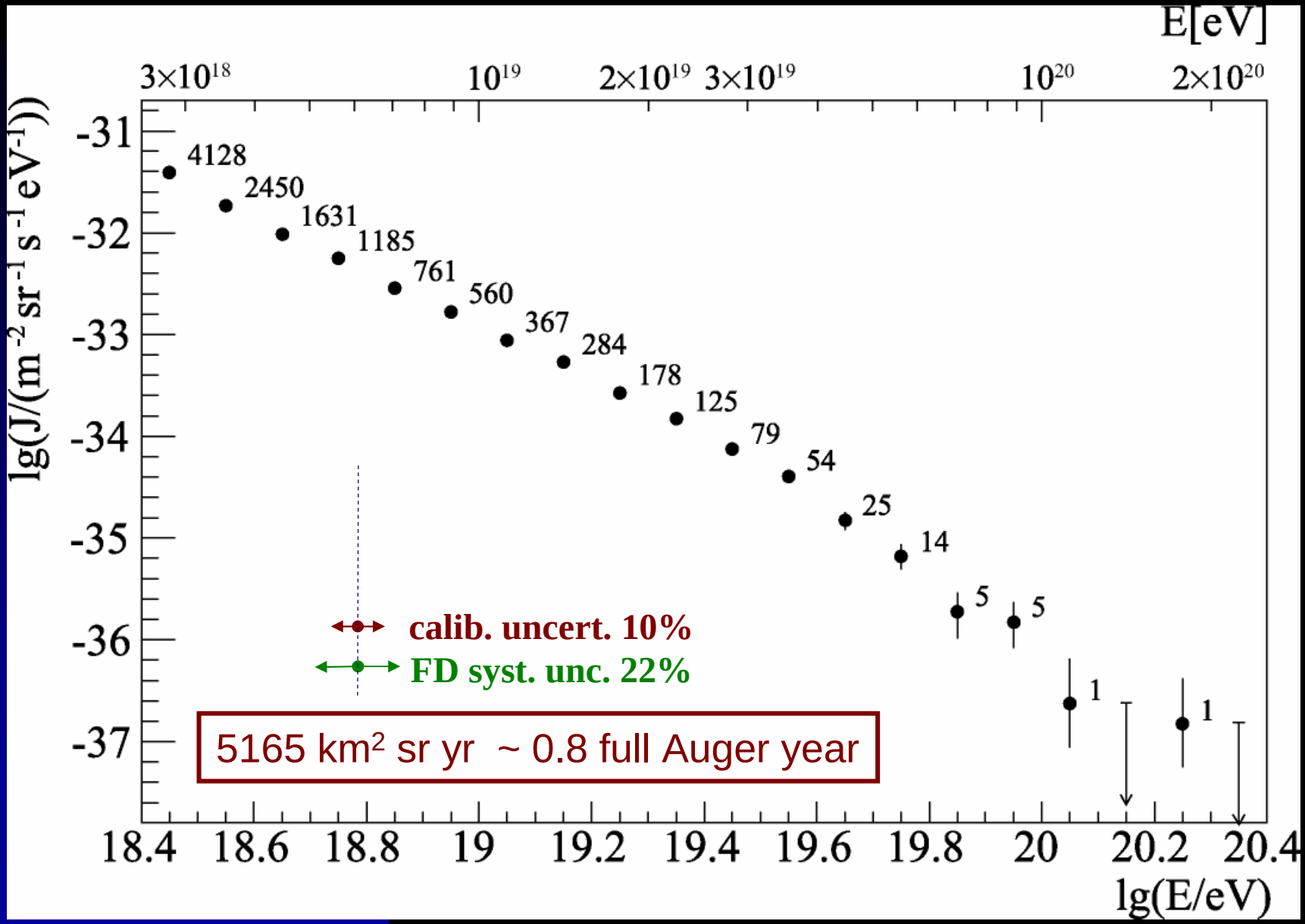
Nagano et al. FY



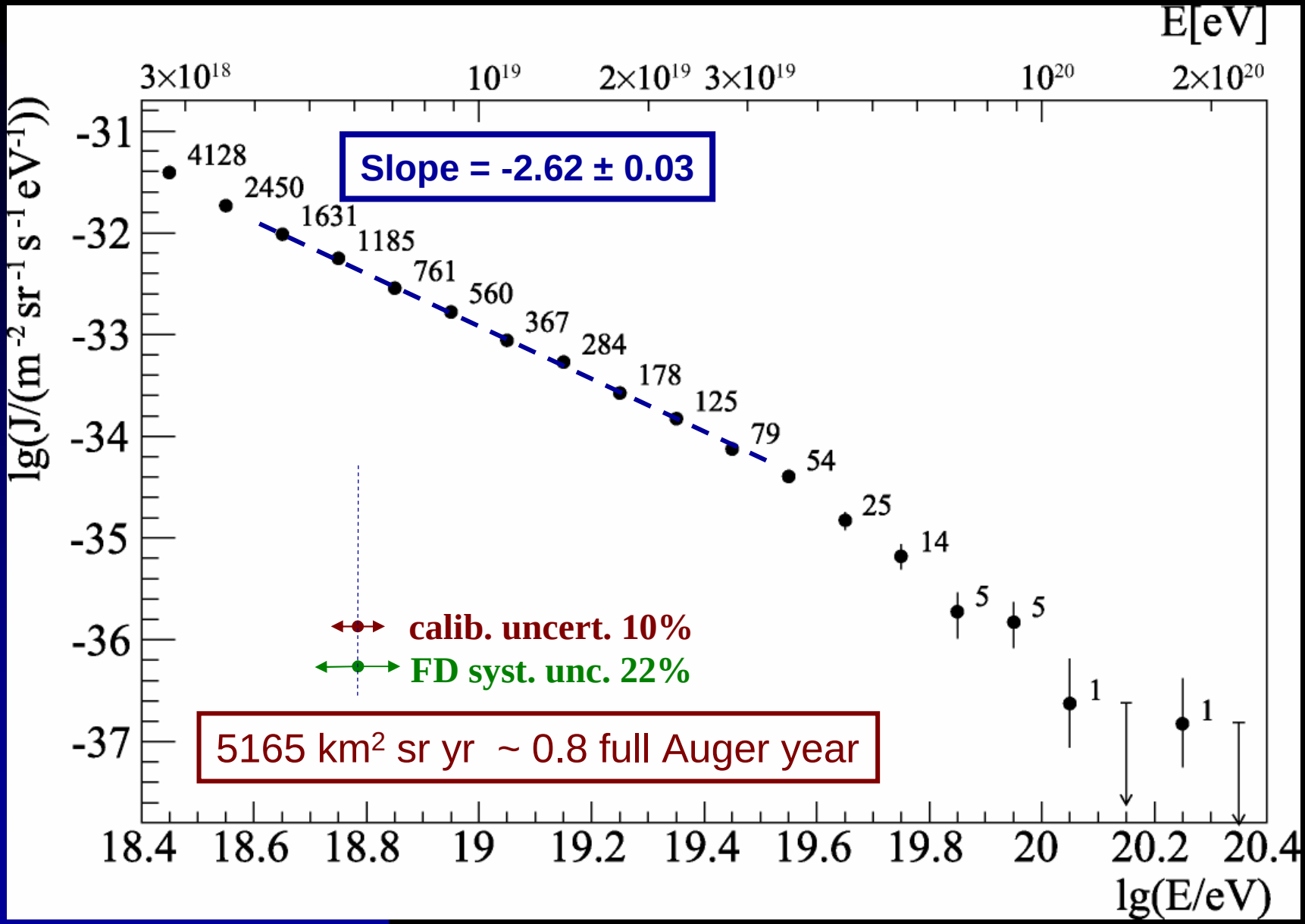


Very good estimator !

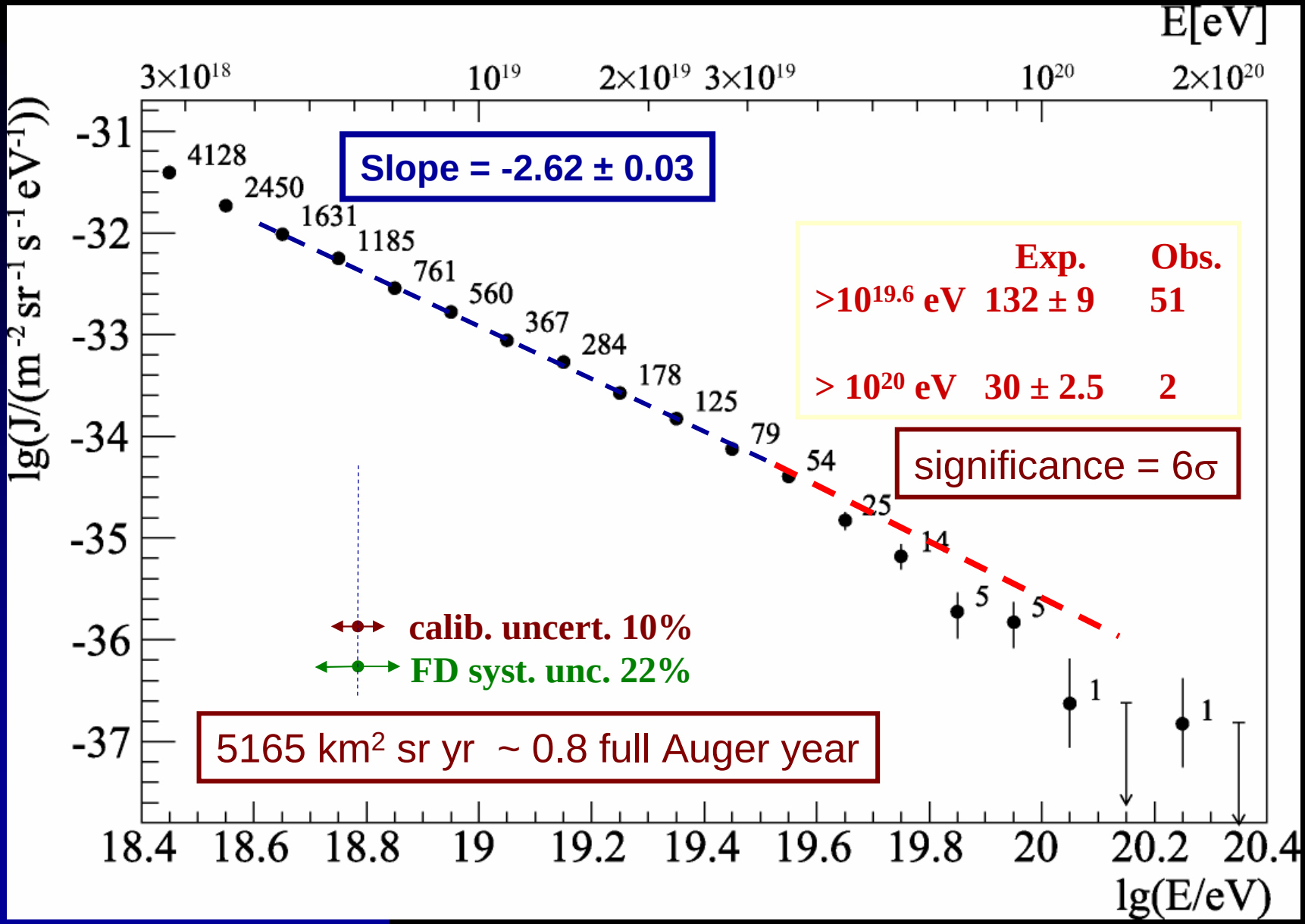
Energy spectrum from SD showers with $\theta \leq 60°$



Energy spectrum from SD showers with $\theta \leq 60°$



Energy spectrum from SD showers with $\theta \leq 60°$



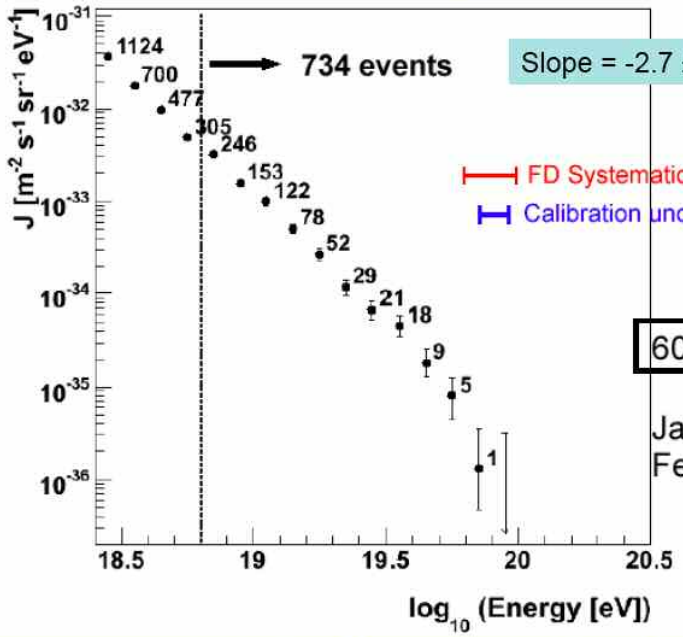
Uncertainty on the energy scale

source	systematic uncertainty
Fluorescence yield	14%
P, T and humidity effects	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
Total:	**22%**

(improvements expected soon…)

Auger Spectra

Inclined events energy spectrum

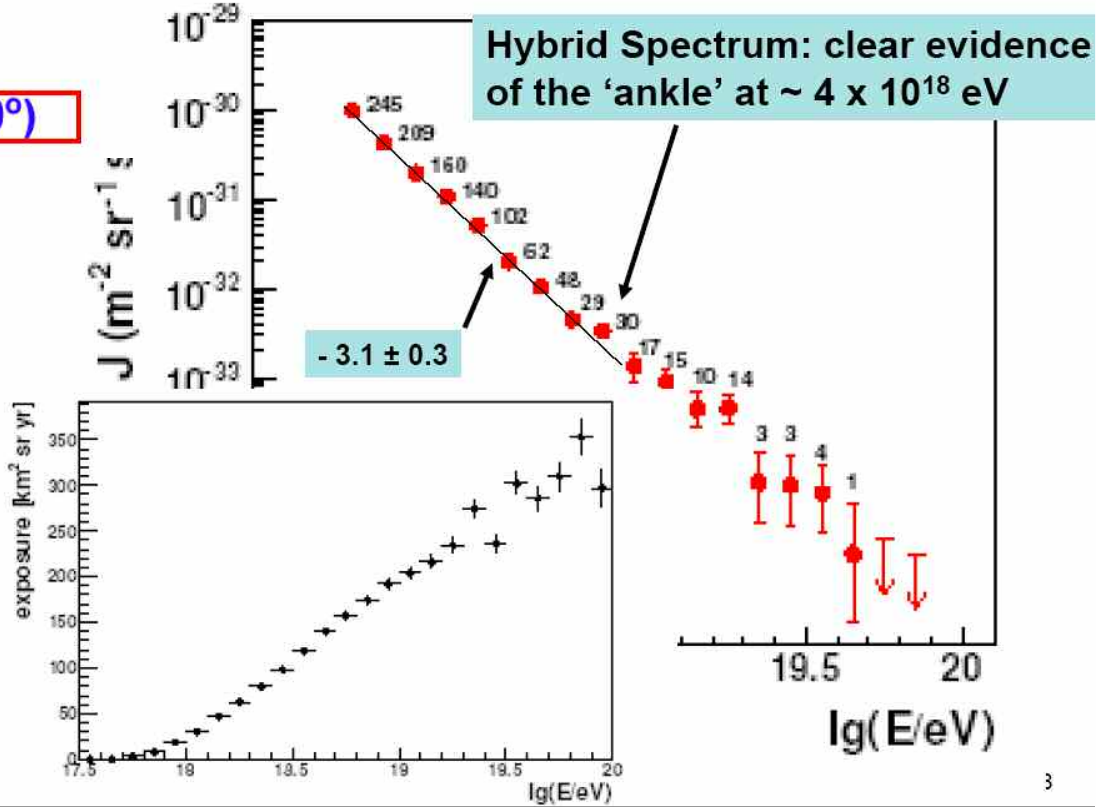


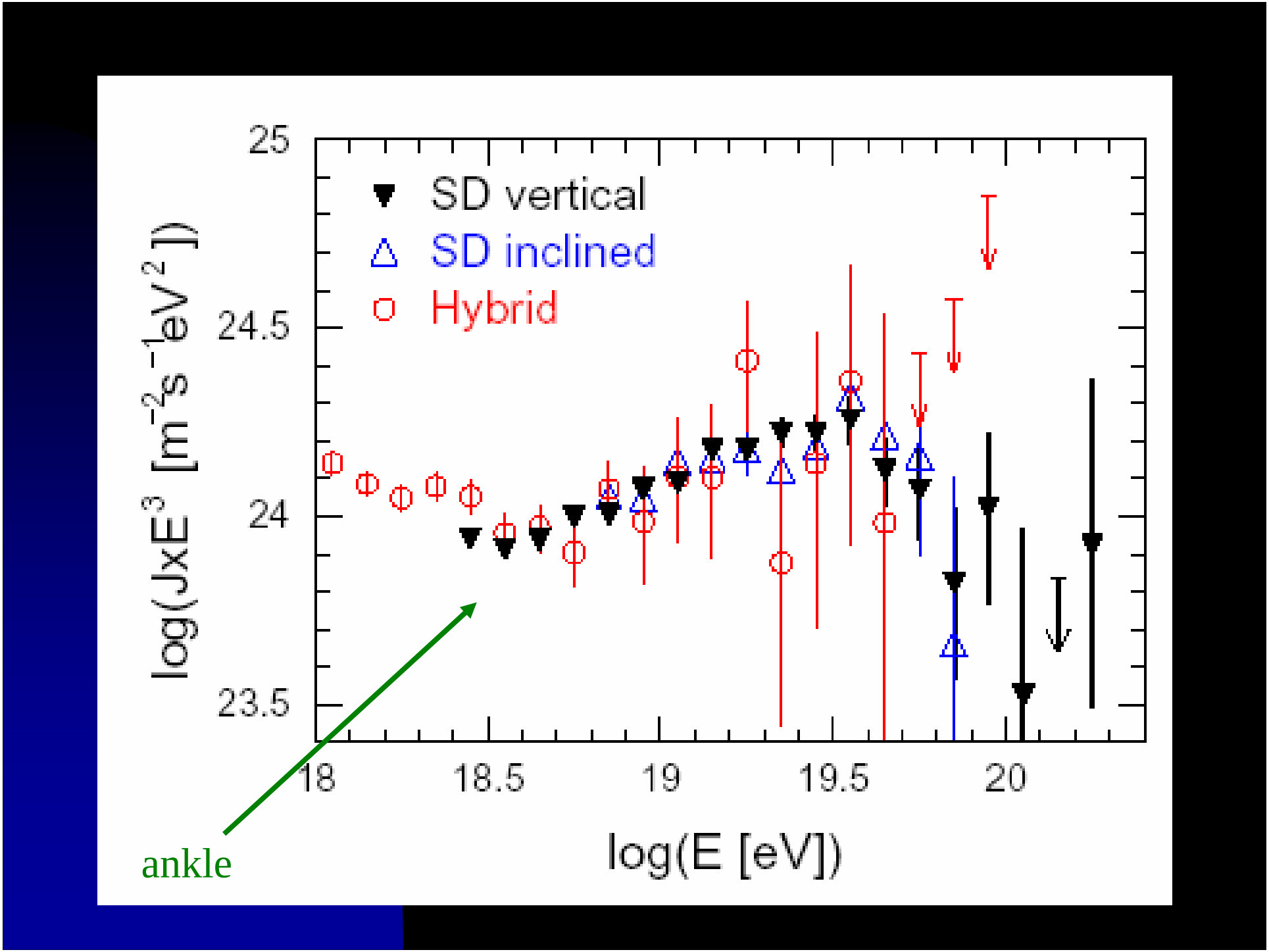
60° < θ < 80°

January 2004 – February 2007

Exposure 1510 km² yr sr (29% of θ<60°)

Hybrid Spectrum: clear evidence of the 'ankle' at ~ 4 x 10^{18} eV




SD vertical
SD inclined
Hybrid
log(JxE^3 [m^-2 s^-1 eV^2])
log(E [eV])
25
24.5
24
23.5
18
18.5
19
19.5
20
ankle

Spectrum facts

There is an ankle

→ How to interpret it?

Galactic/Extragalactic transition?

or

Spectral feature from pair-production energy losses of pure-proton UHECRs?

→ analyse composition!

There is a “cut-off”

→ How to interpret it?

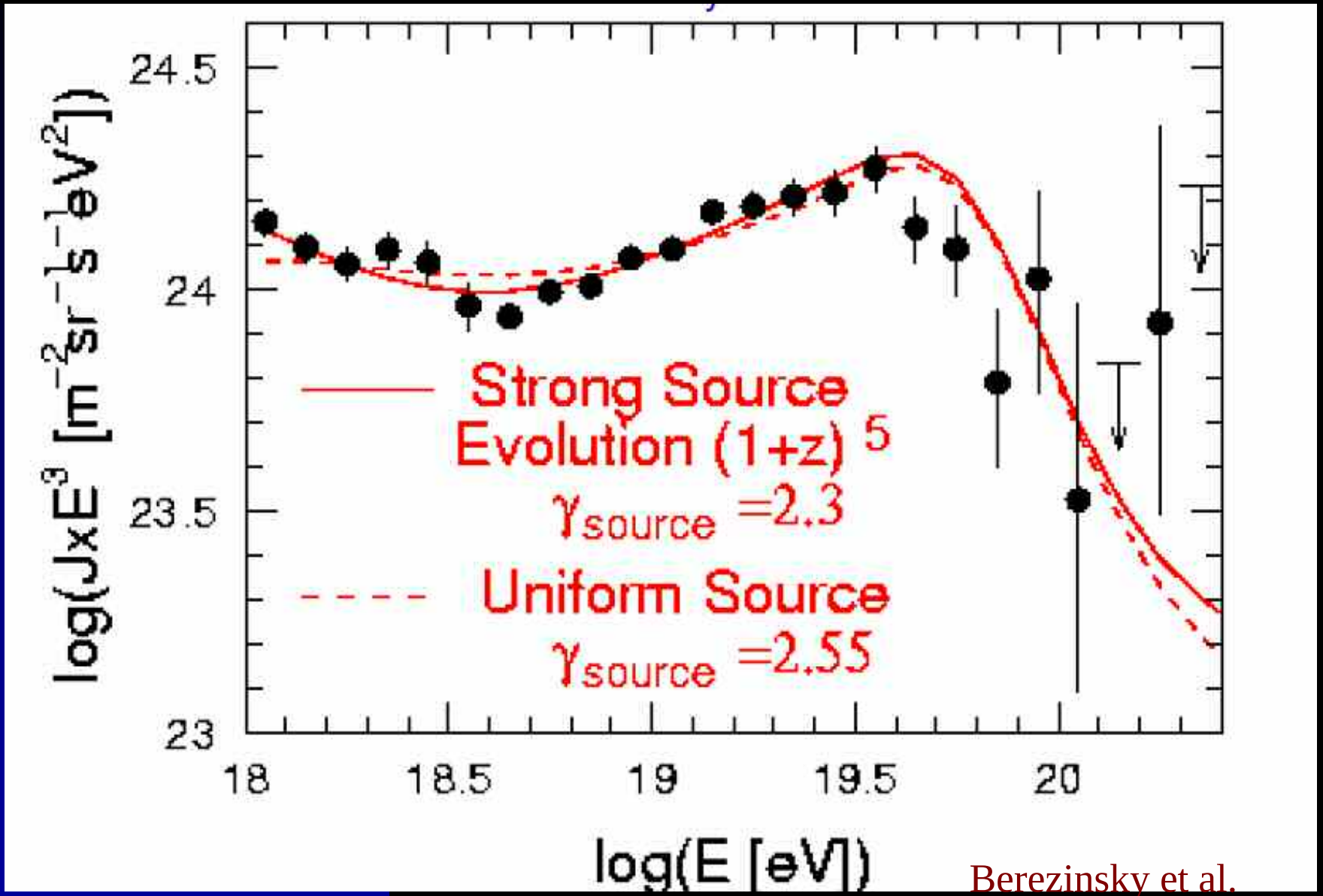
GZK suppression?

or

Limit of the acceleration process?

→ analyse arrival directions!

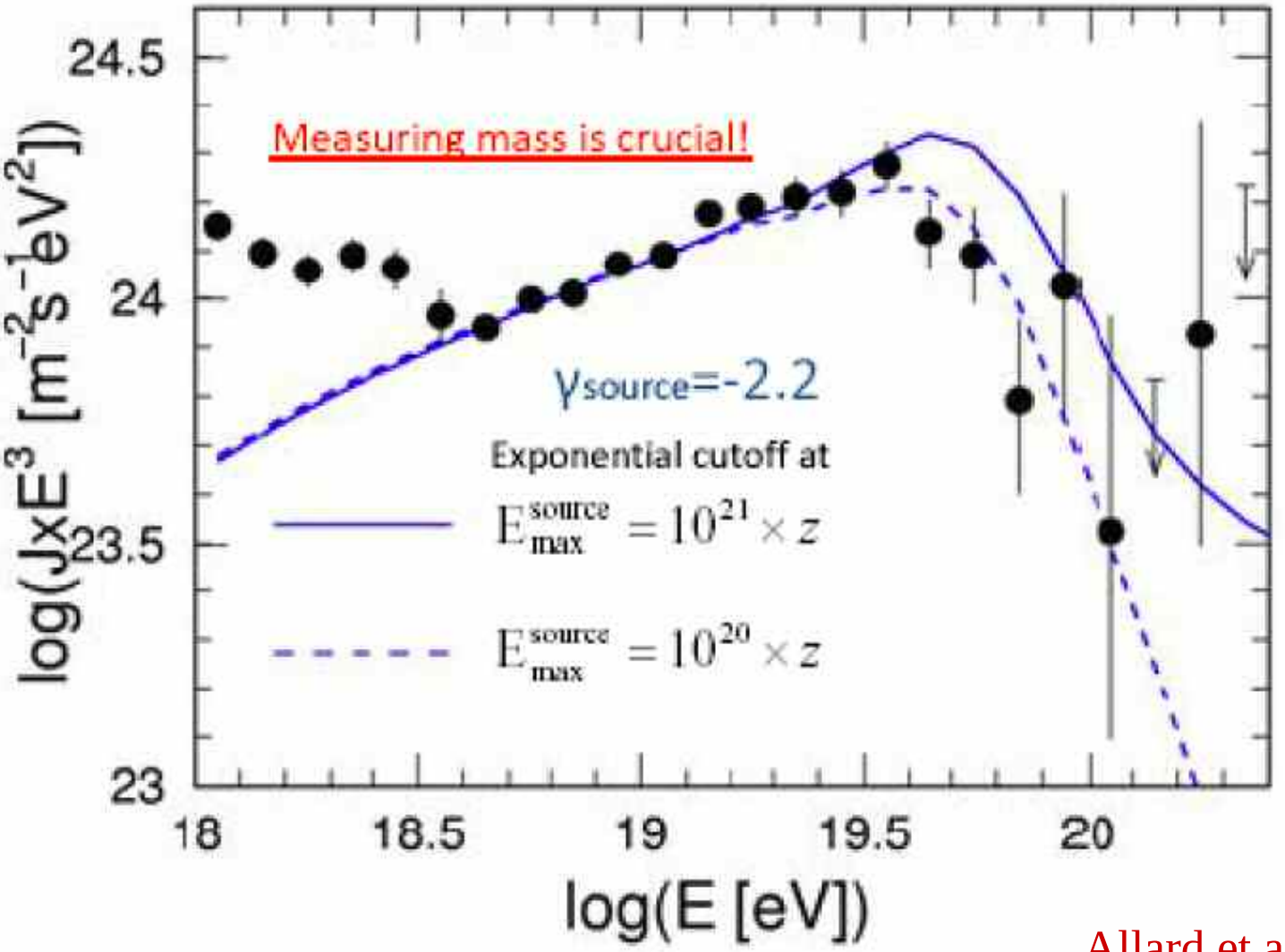
Ankle as Pure Proton e^+e^- dip



Berezinsky et al.

Nucleus Model

CR abundance is same as low energy Galactic components



Allard et al.

Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

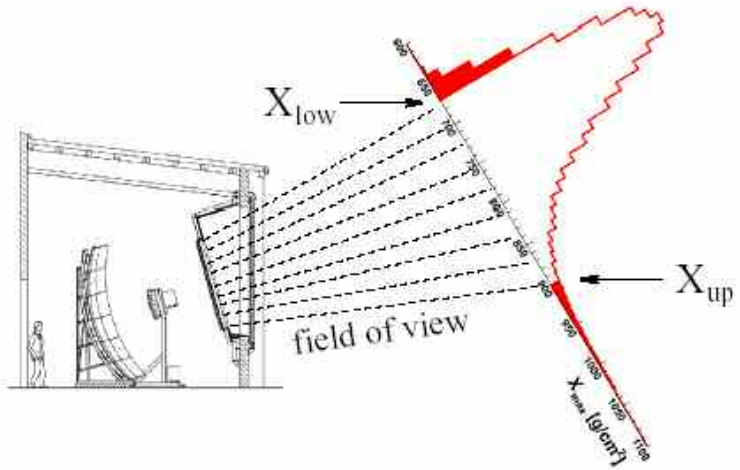
features? ankle, GZK; injection? Propagation?

Composition

protons, nuclei, photons, neutrinos

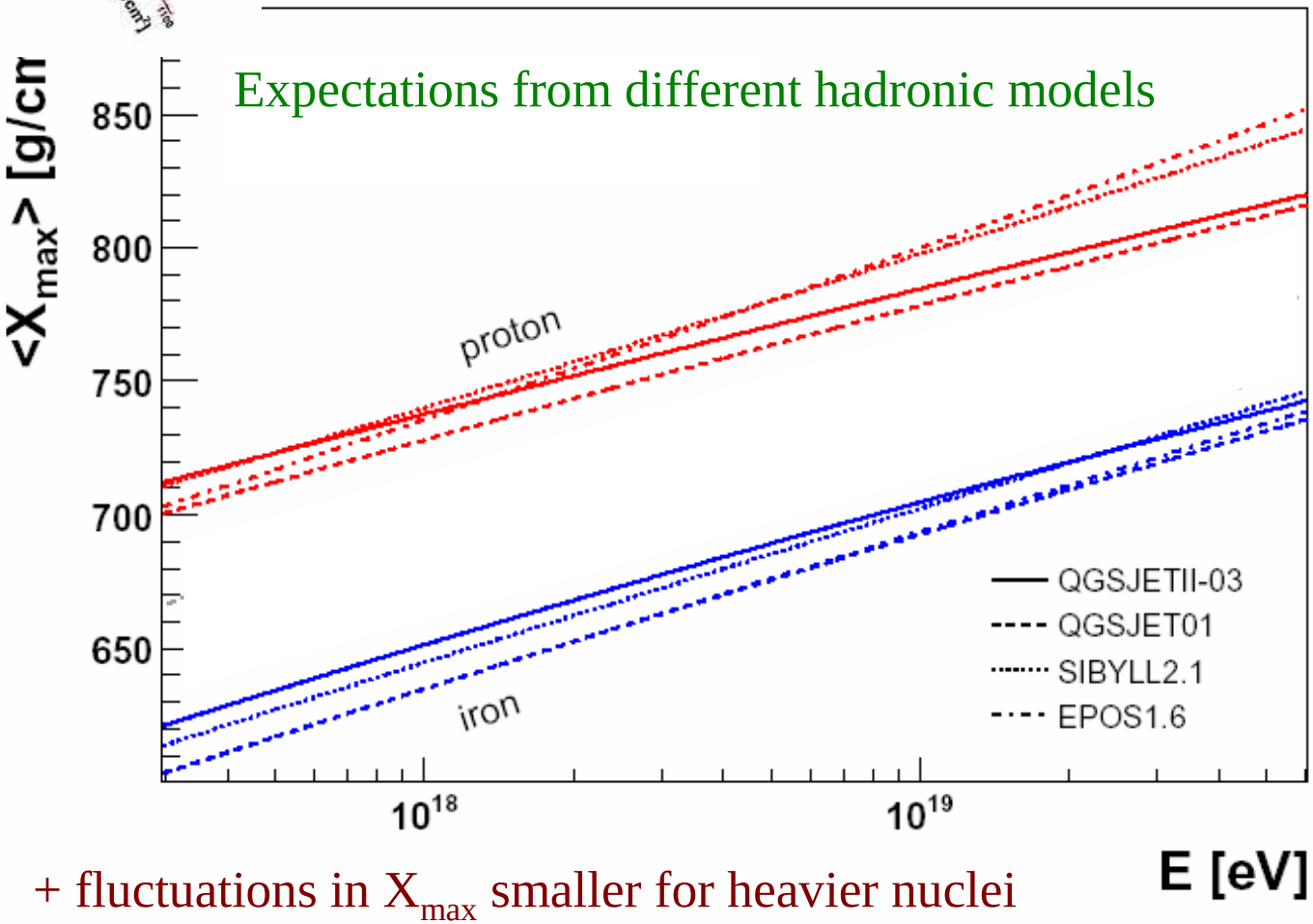
Arrival Direction Distribution

anisotropies?



Composition observable: shower maximum

Expectations from different hadronic models

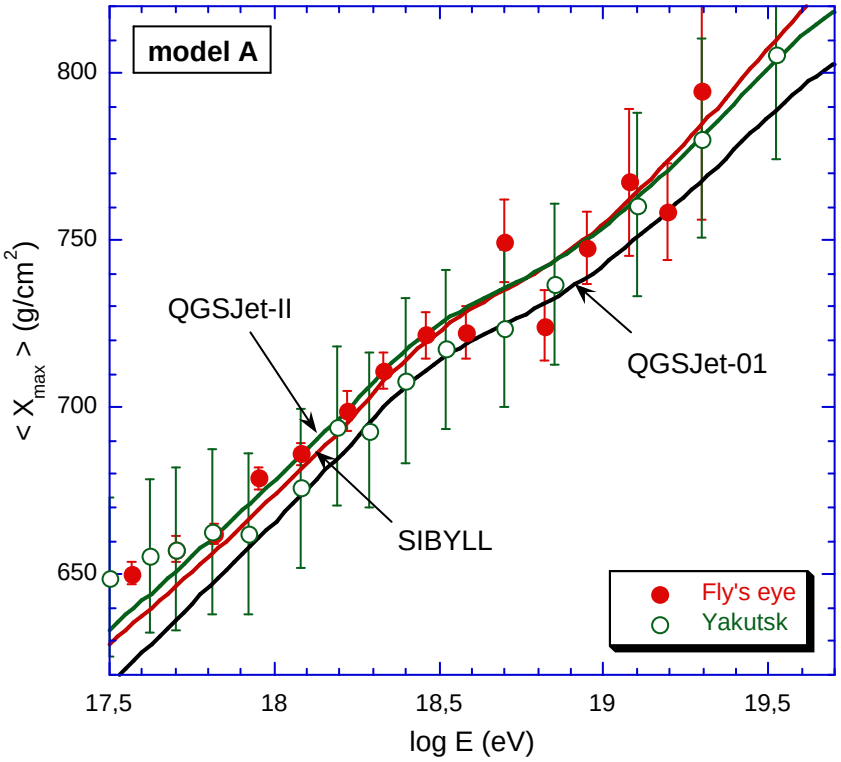


+ fluctuations in X_{max} smaller for heavier nuclei

Injection Model Predictions

(Galactic/Extragalactic transition)

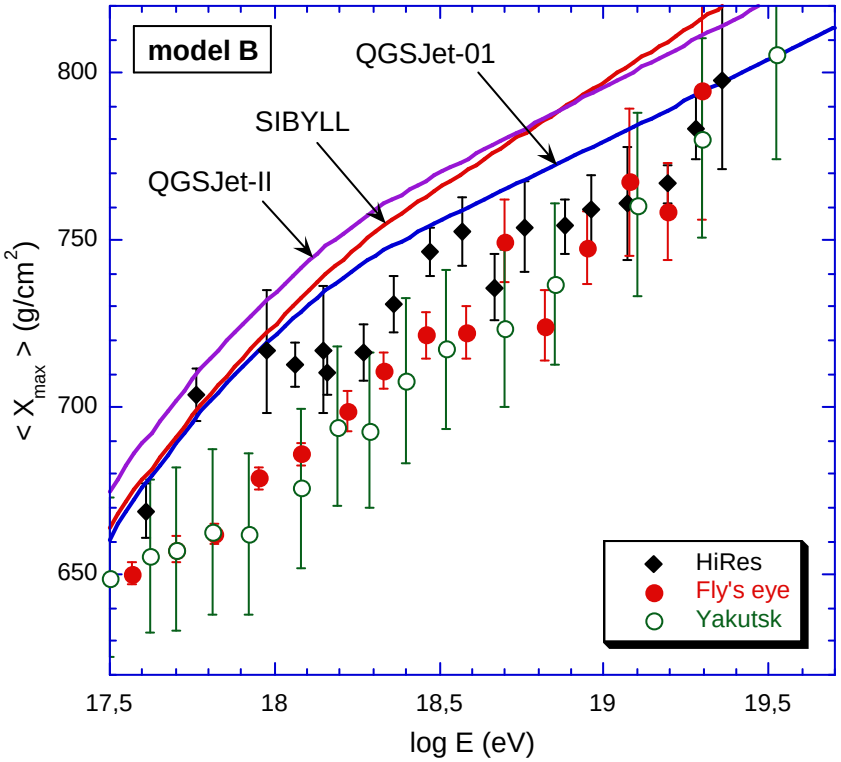
Mixed composition (Allard et al.)



Source spectrum in $E^{-2.3}$

Ankle = Gal./extragal. transition

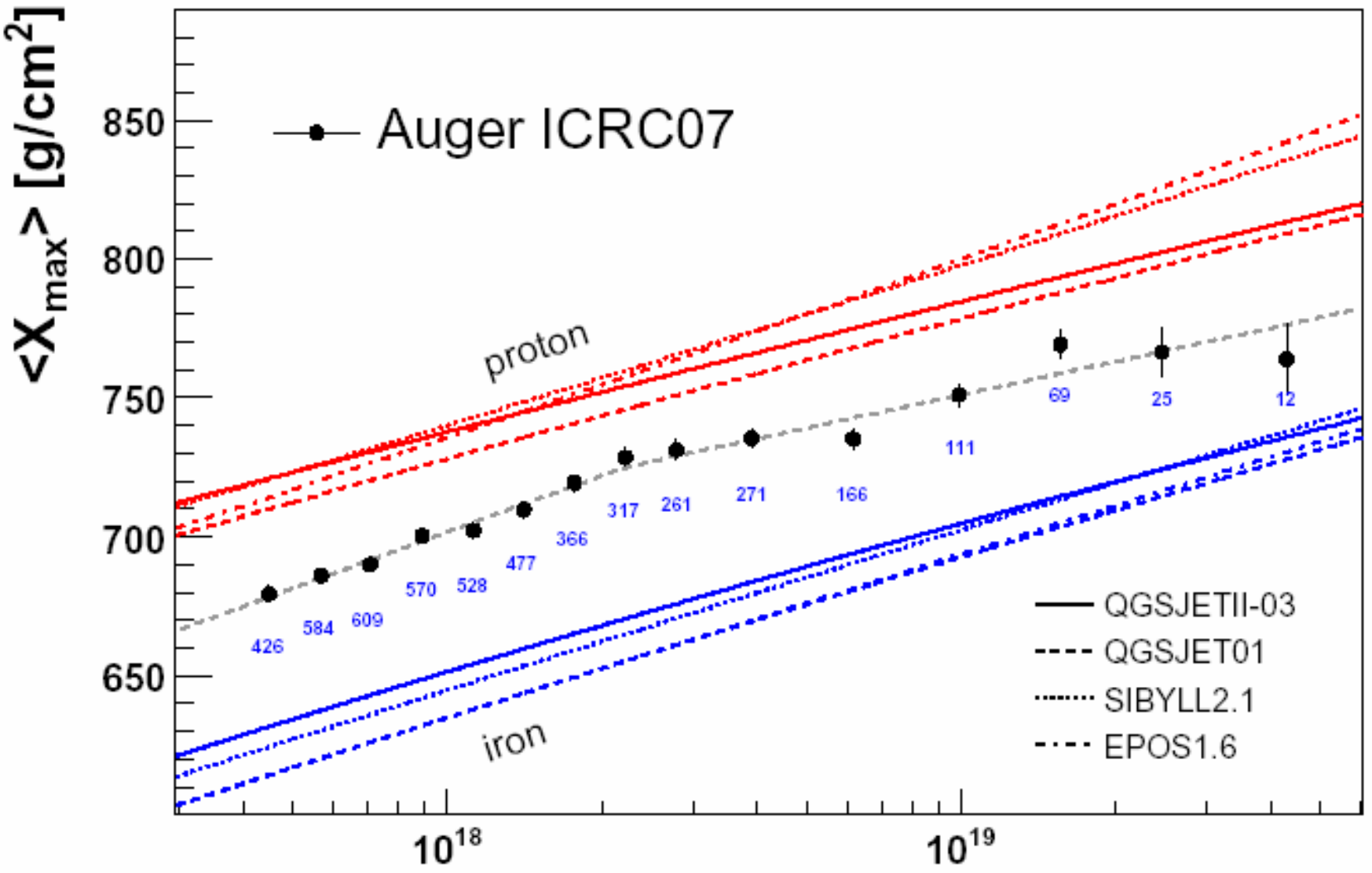
Pure protons (Berezinsky et a)l



Source spectrum in $E^{-2.6}$

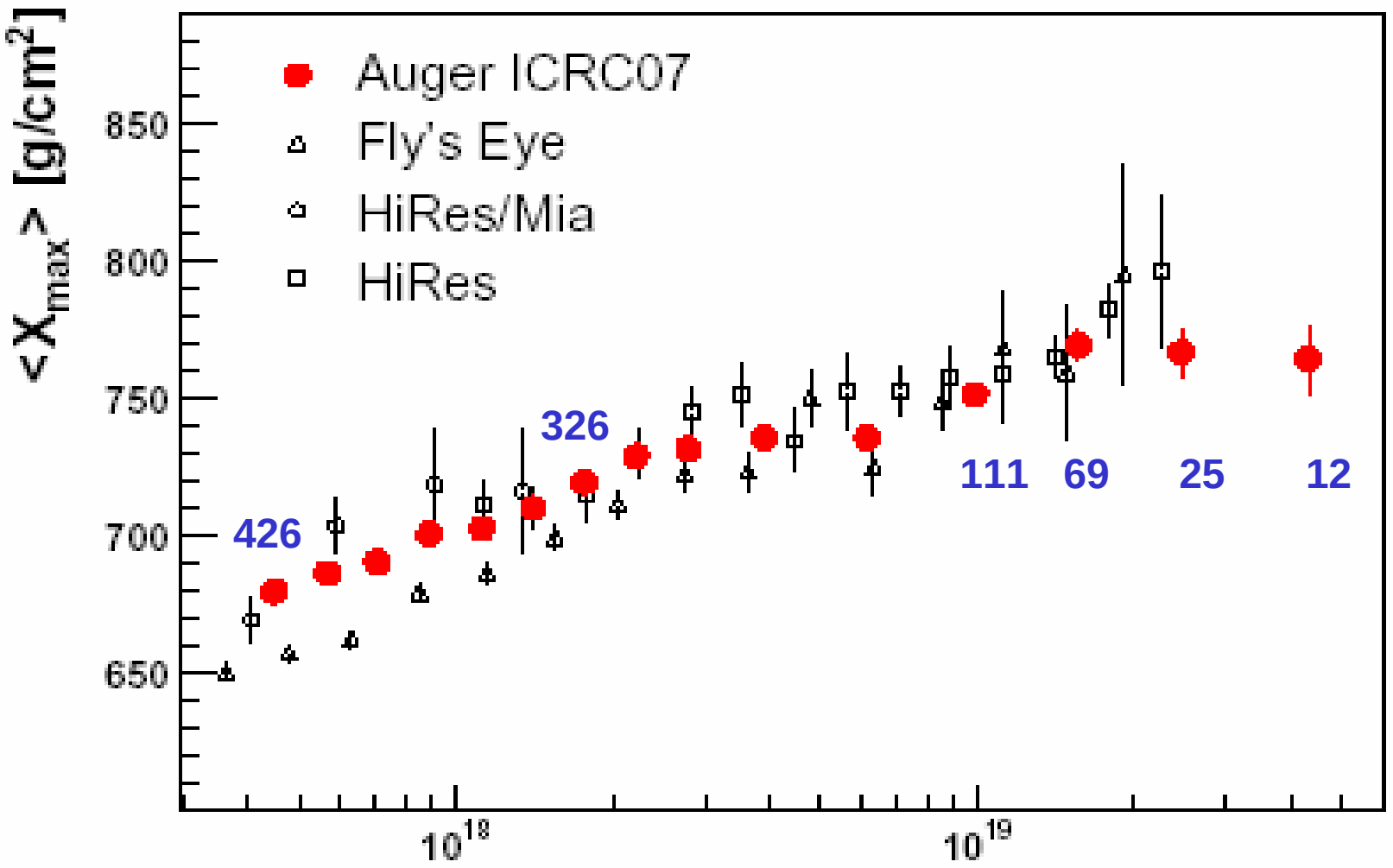
Ankle = "pair production dip"

Shower maximum over 2 decades in E



+ fluctuations in X_{max} to be exploited

Comparison with previous studies



Large number of events allows good control and understanding of systematics

Photon limit

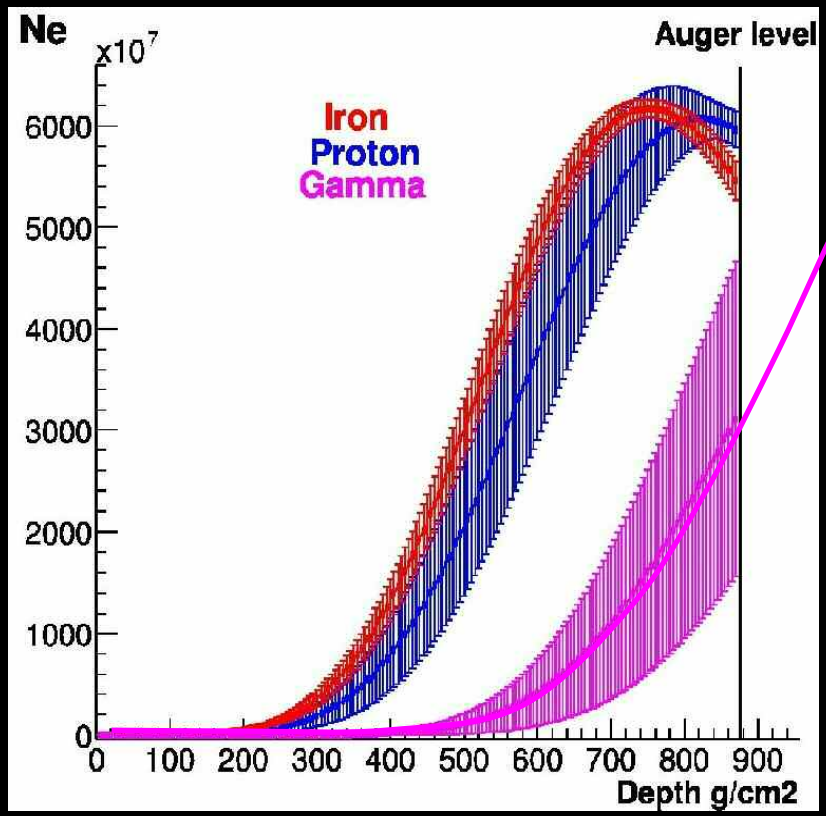
Top-down models predict large UHE photon flux

SHDM models: decay of super-heavy dark matter accumulated in Galactic halo

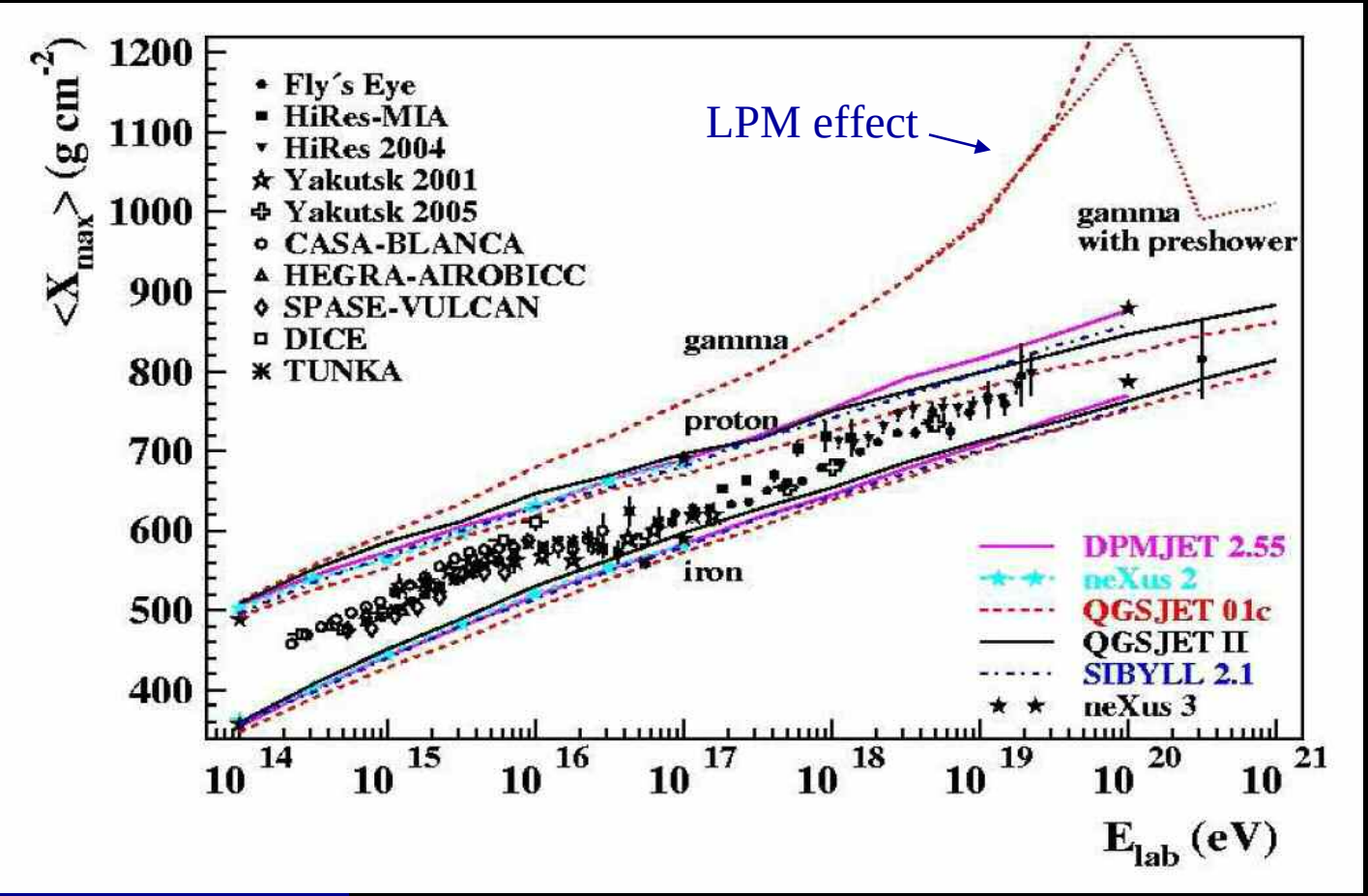
TD models: supermassive particle decay from topological defect interaction or annihilation

Photon-induced showers look very different

Showers at $E = 10^{19}$ eV, $\theta = 0°$:



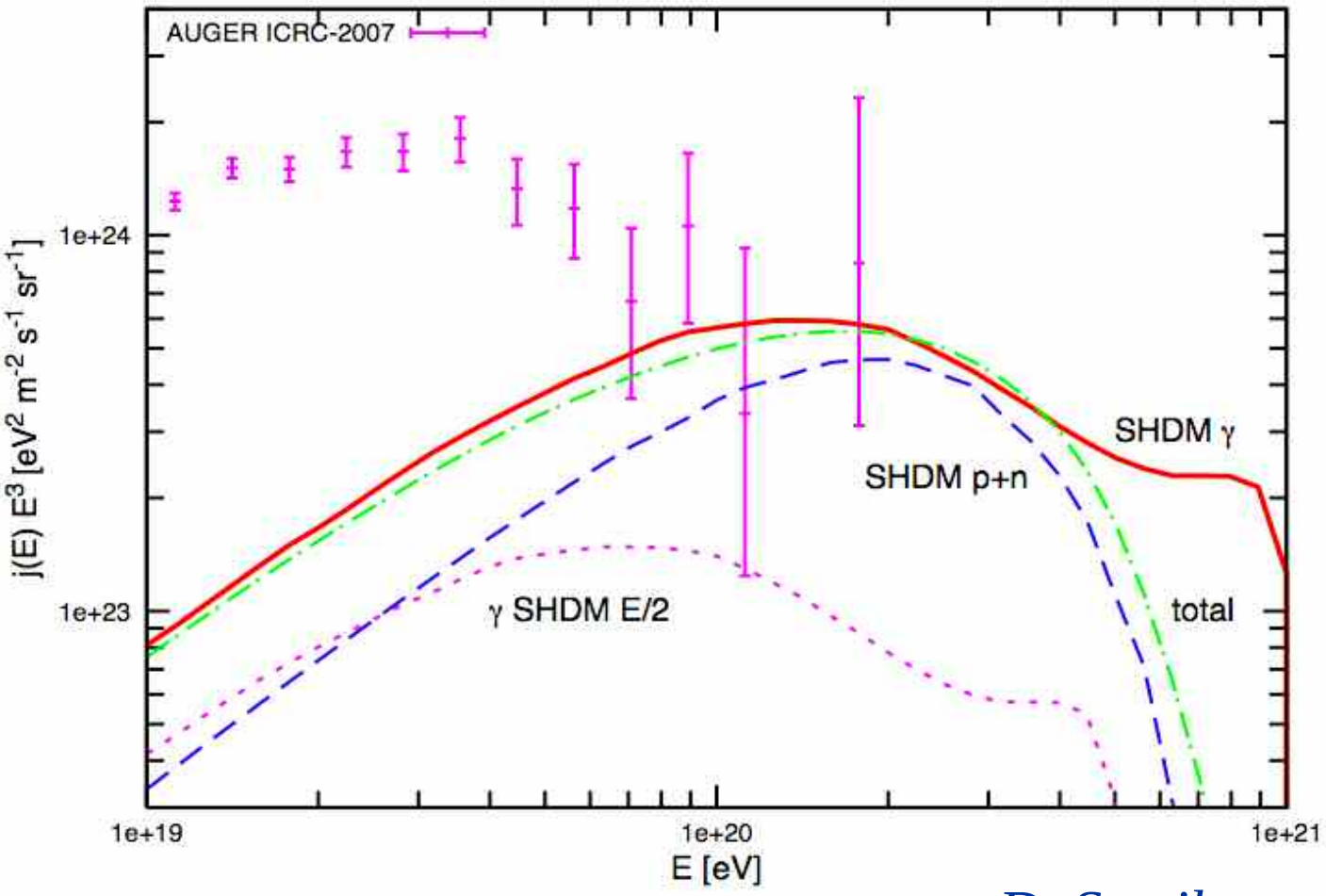
Photon limit



Larger X_{max}: photon showers delayed by > 200 g/cm^2 at 10^{19} eV

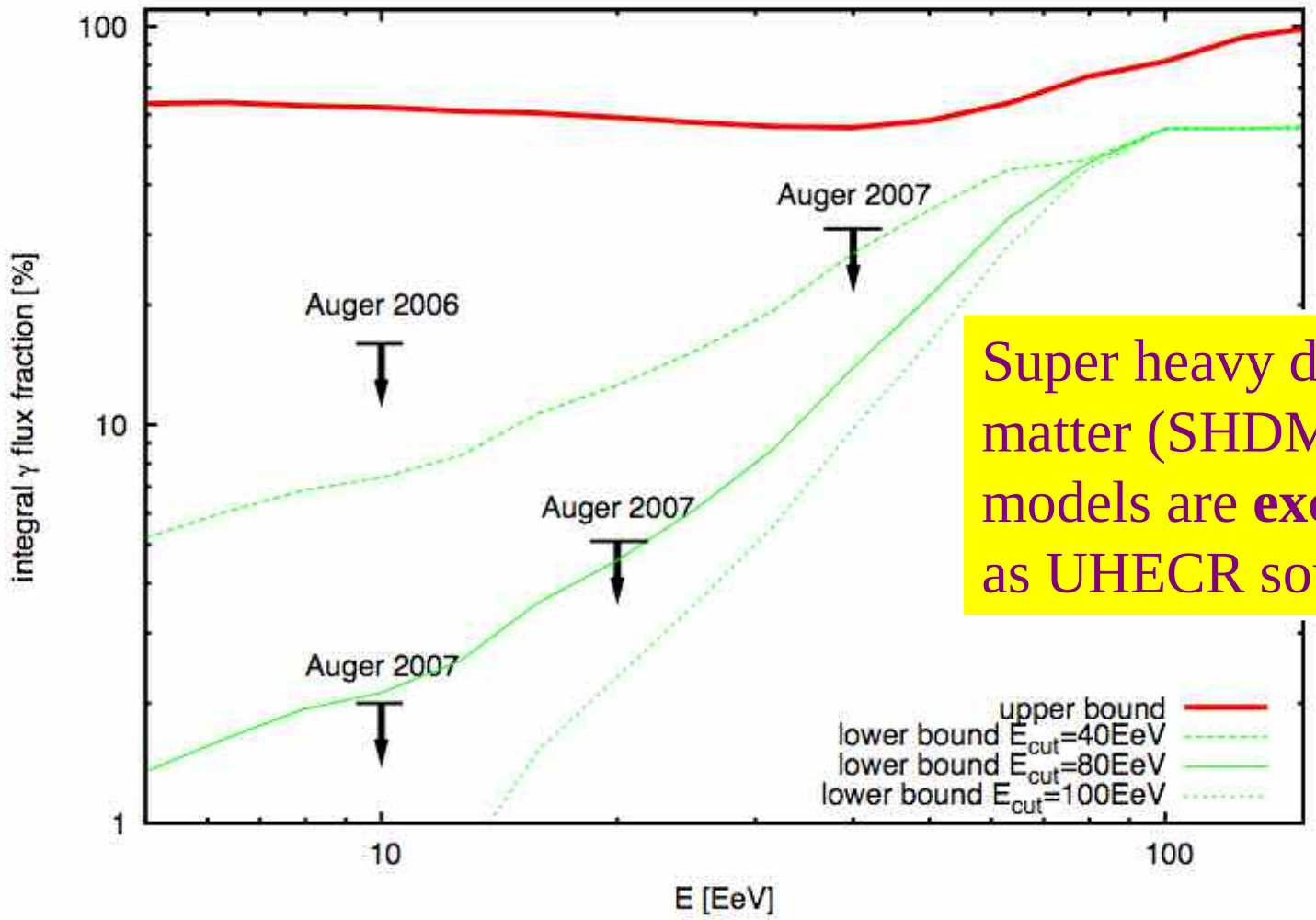
⟹ ≠ SD observables: { smaller rise time of the signals
smaller radius of curvature of the shower front

Constraints on Super-Heavy Dark Matter as sources of UHECRs



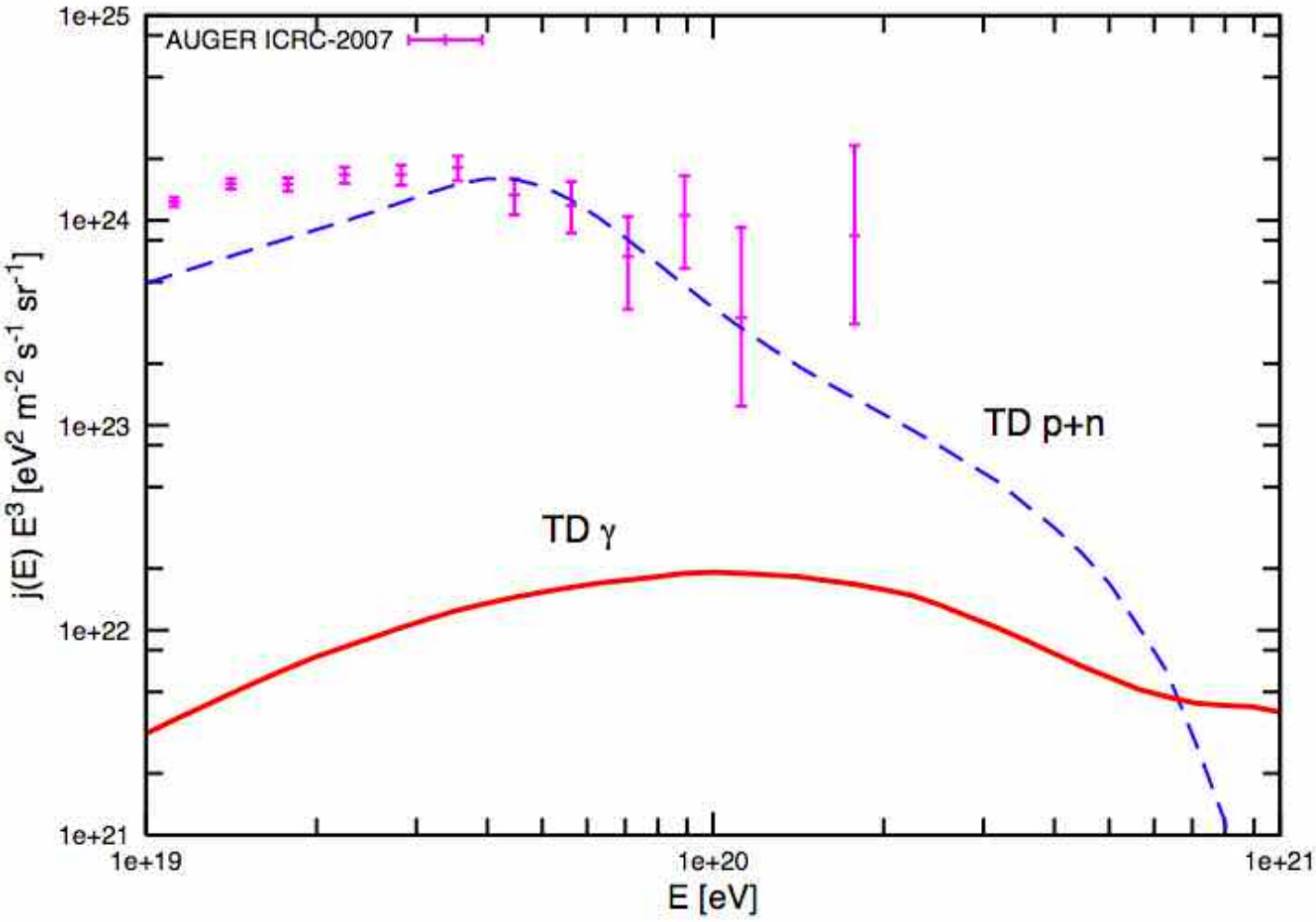
see D. Semikoz

Auger results (photon limit)

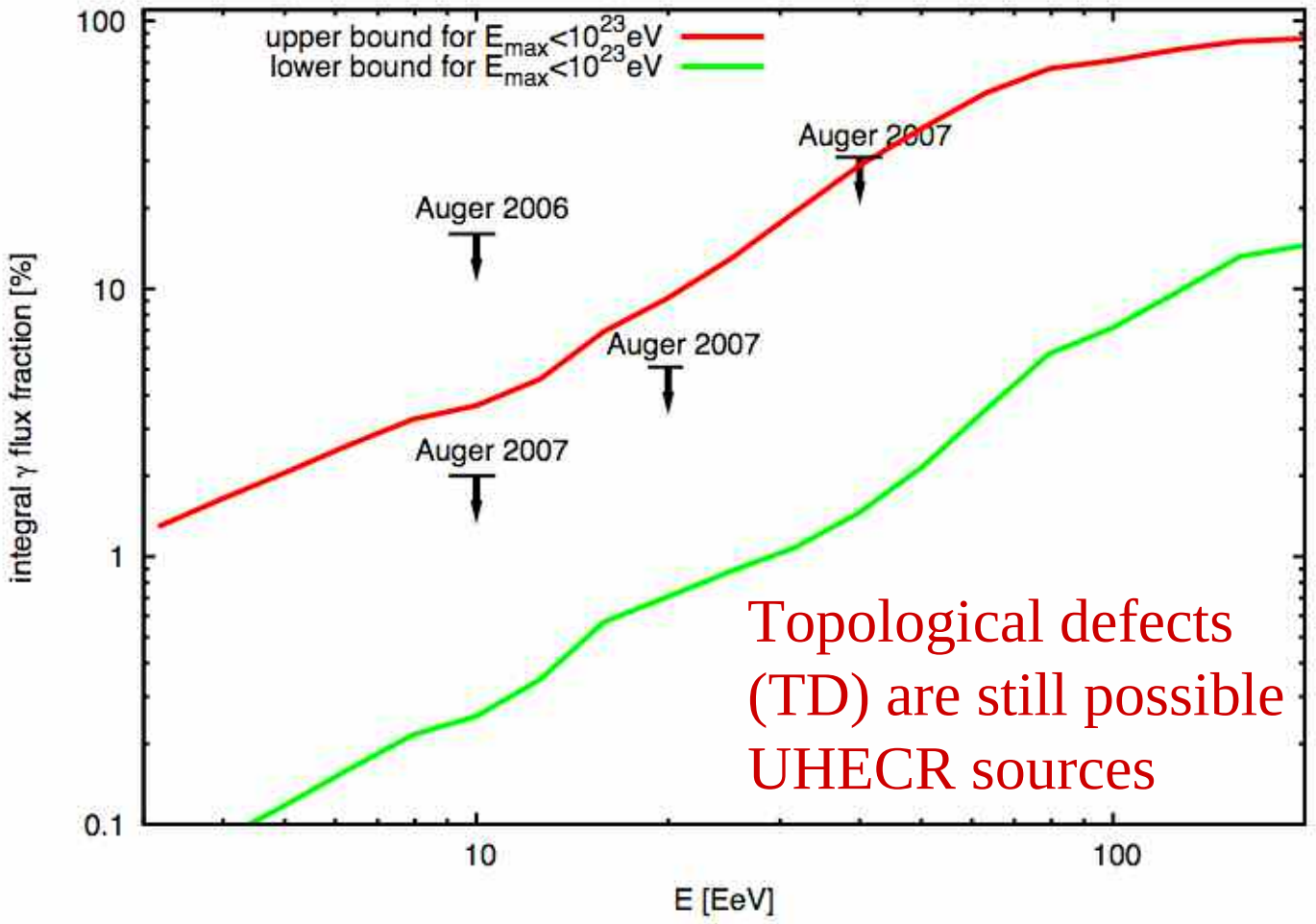


Super heavy dark matter (SHDM) models are **excluded** as UHECR sources!

Constraints on topological defects as sources of UHECRs



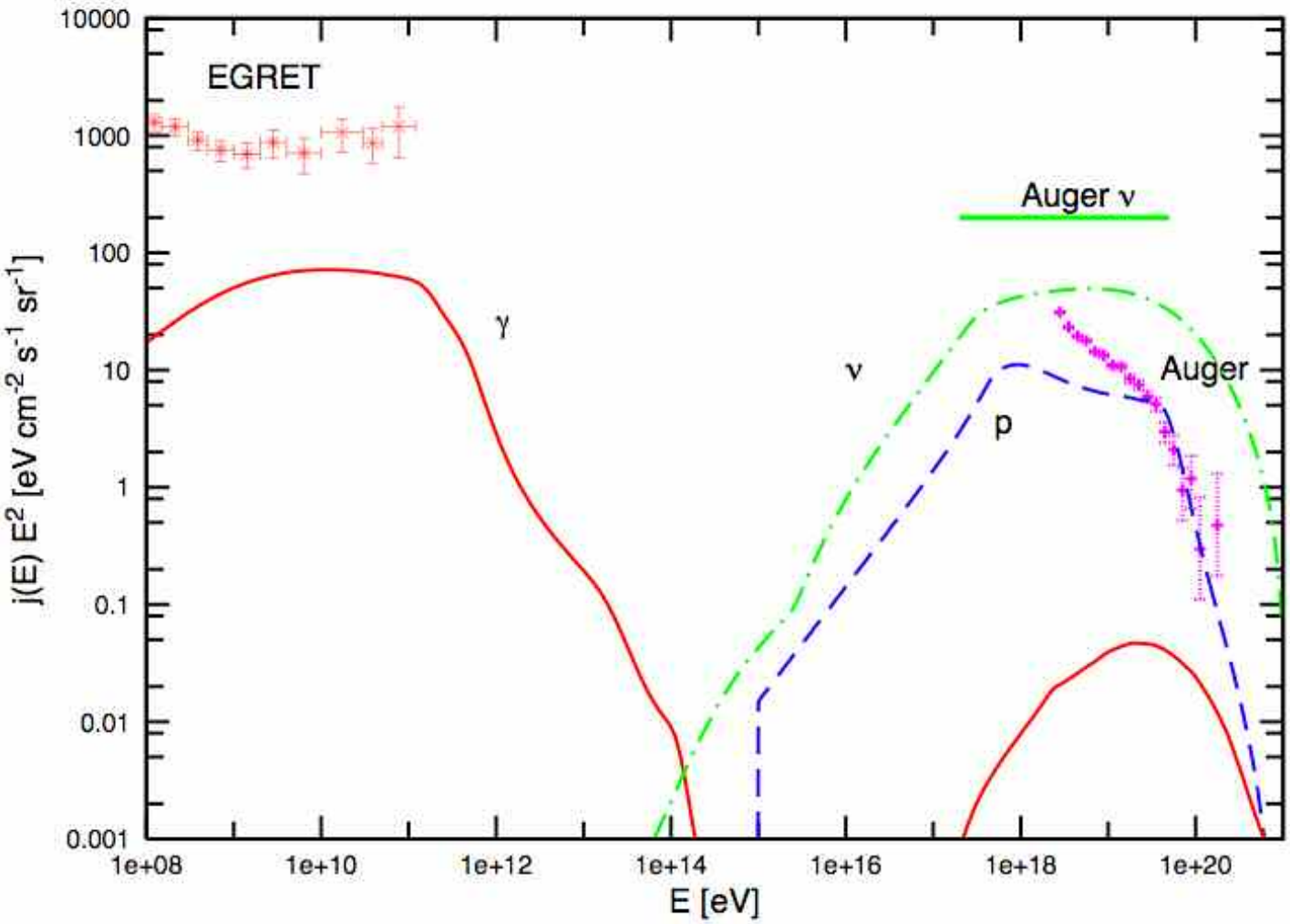
Auger results (photon limit)



Topological defects (TD) are still possible UHECR sources

Auger results

TD models closer to be constrained by Auger neutrino limits



Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

features? ankle, GZK; injection? Propagation?

Composition

protons, nuclei, photons, neutrinos

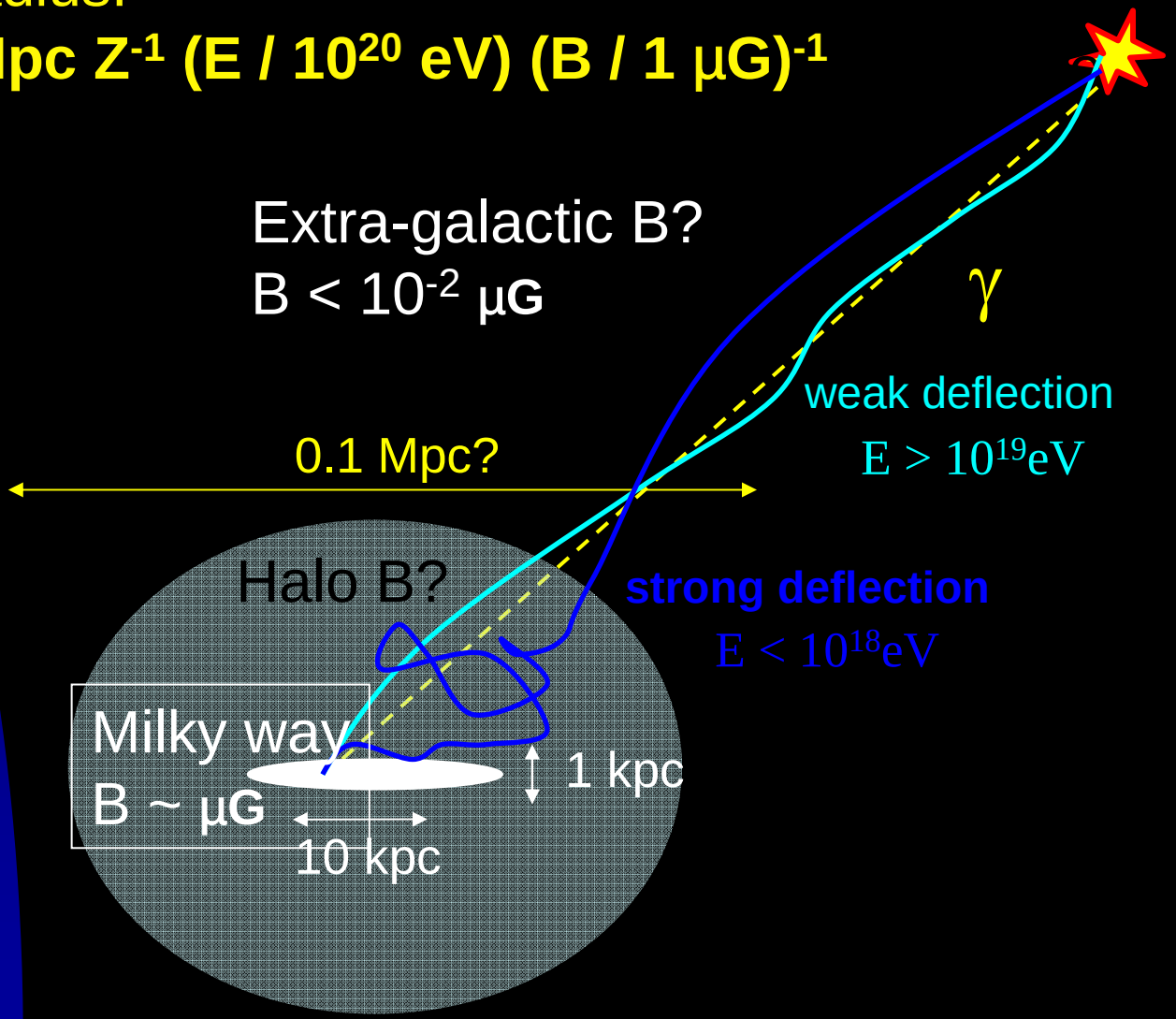
Arrival Direction Distribution

anisotropies?

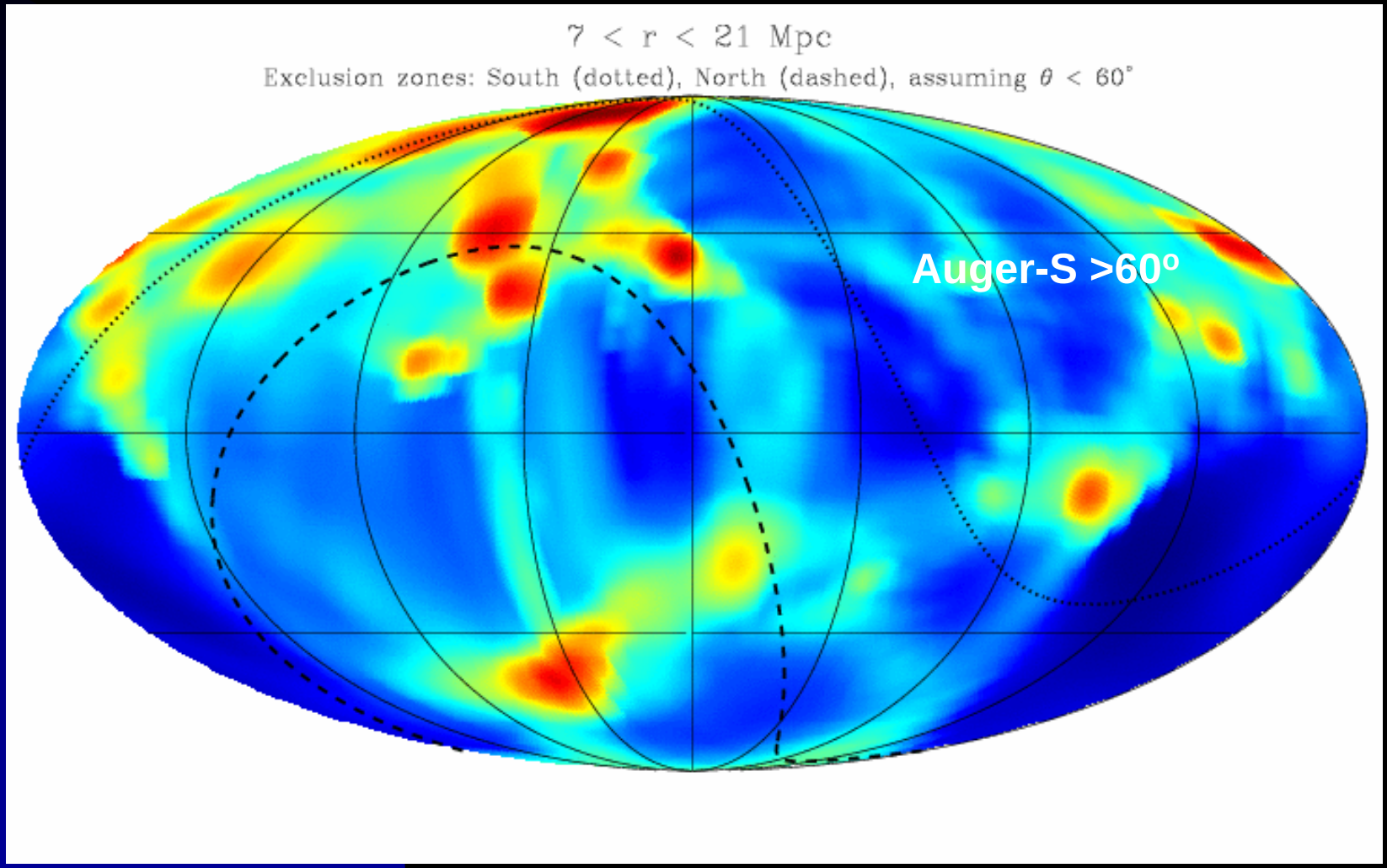
Cosmic Magnetic Fields

Larmor radius:

$r_L = 0.1\ \mathrm{Mpc}\ Z^{-1}\ (E / 10^{20}\ \mathrm{eV})\ (B / 1\ \mu\mathrm{G})^{-1}$



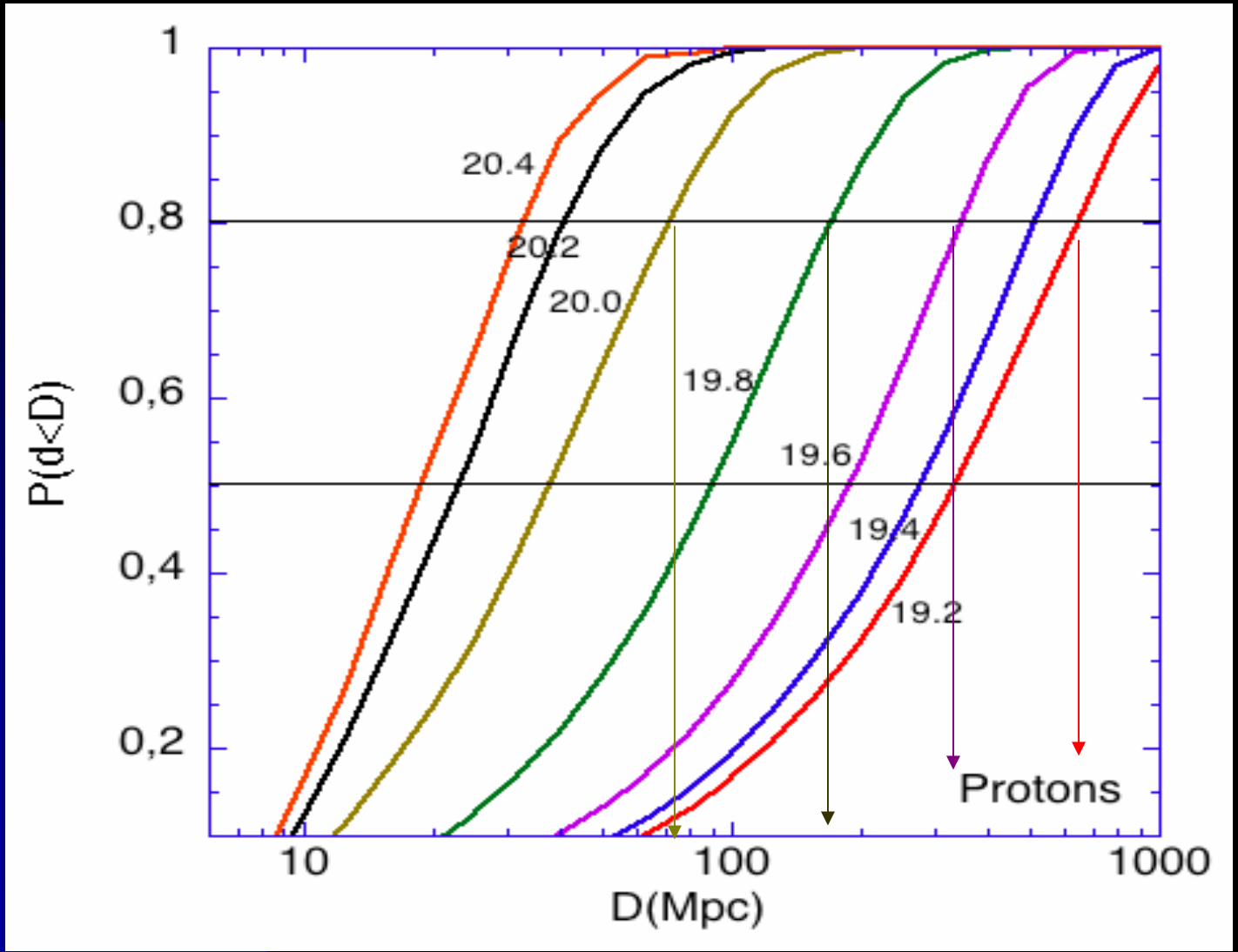
Dark Matter within 20 Mpc



Galactic Center in the Center!!!

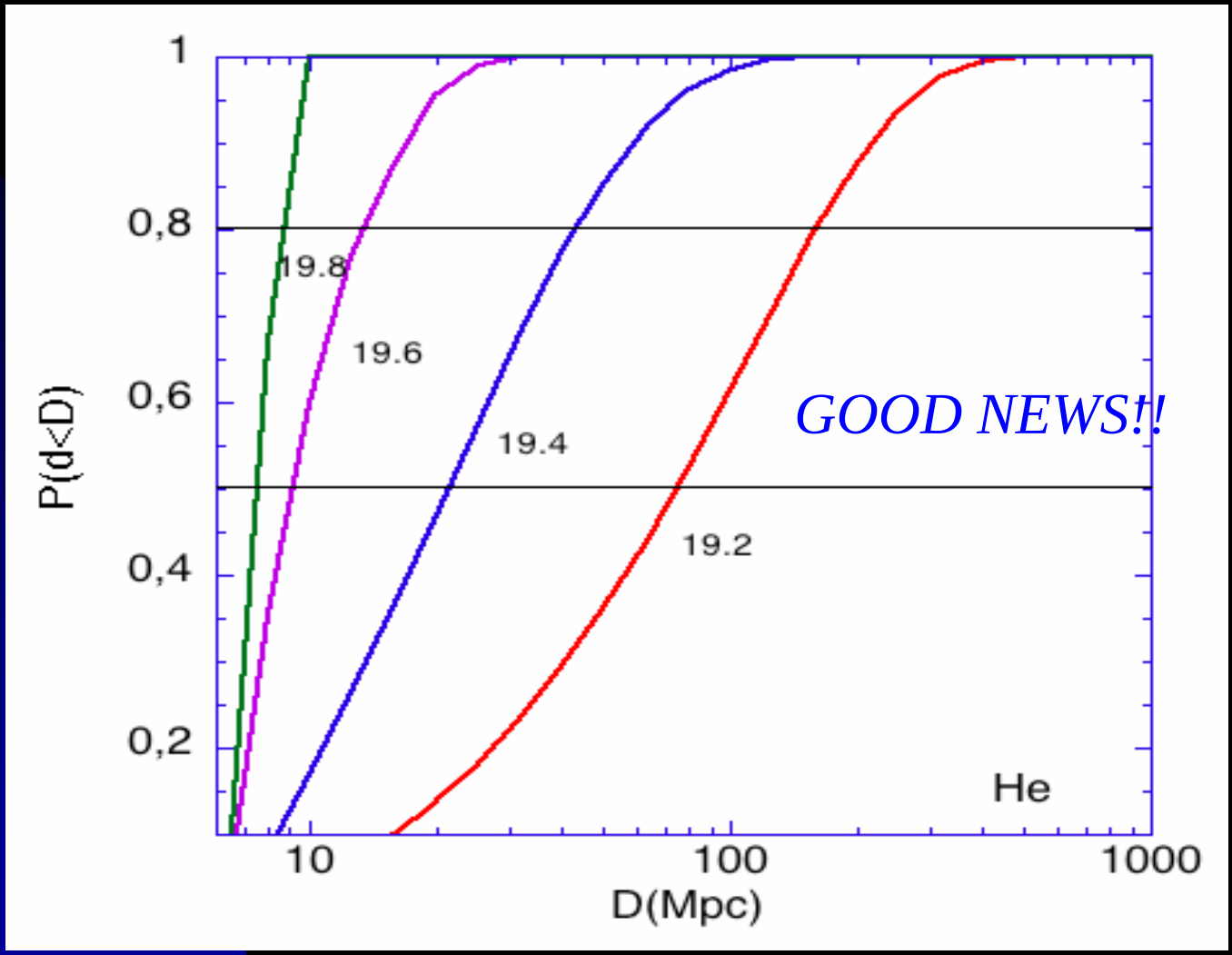
Kravtsov, Armengaud

Proton Horizon



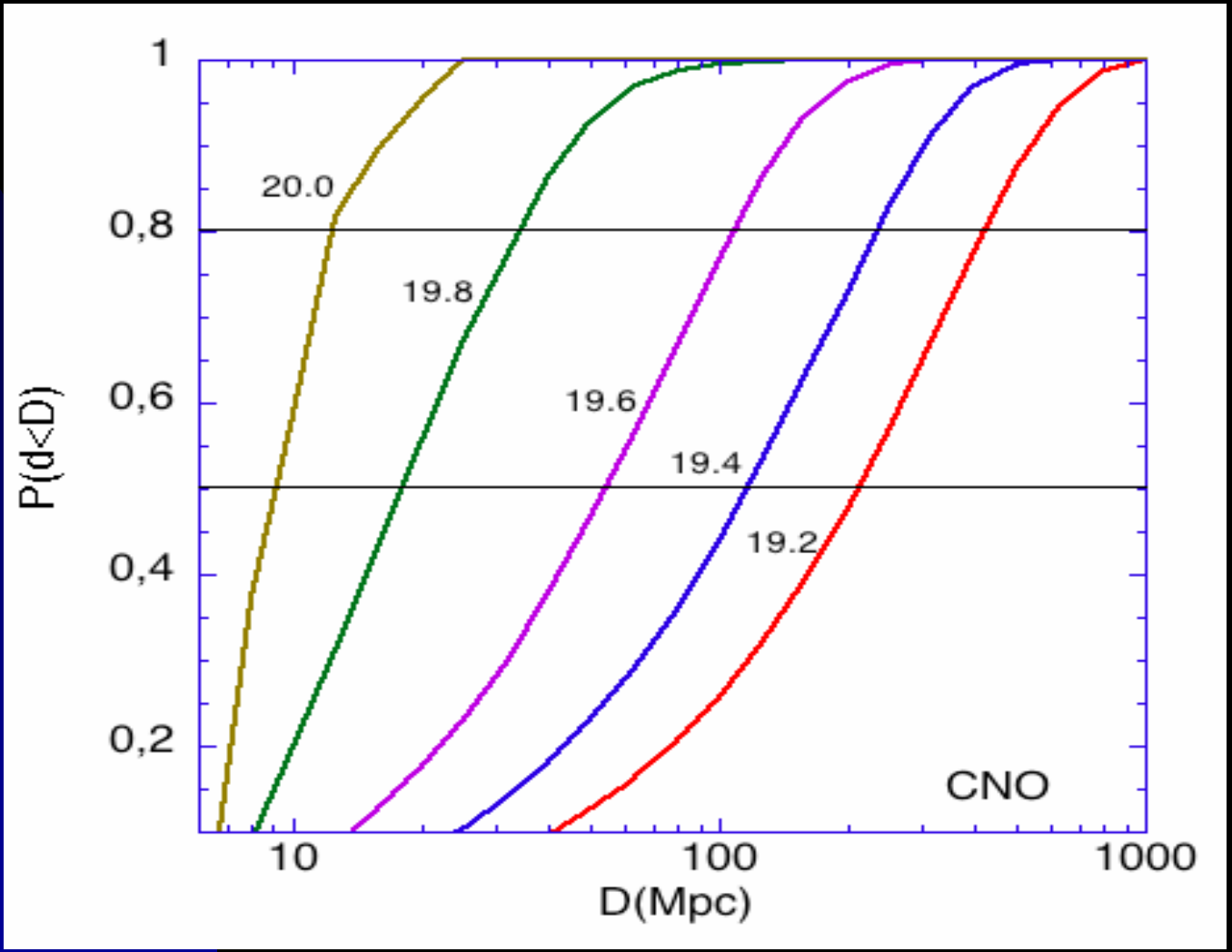
Allard

Helium Horizon



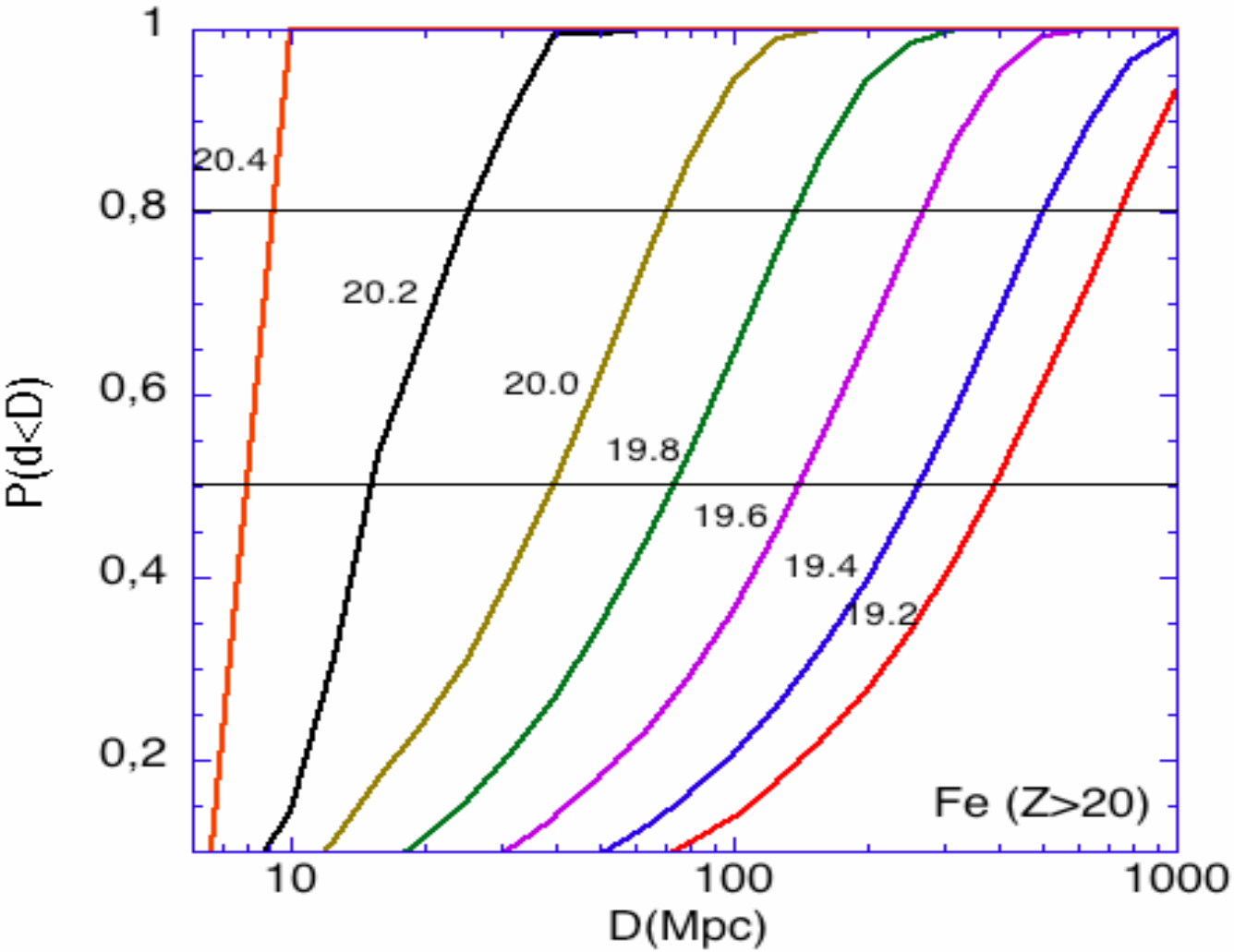
Allard

CNO Horizon



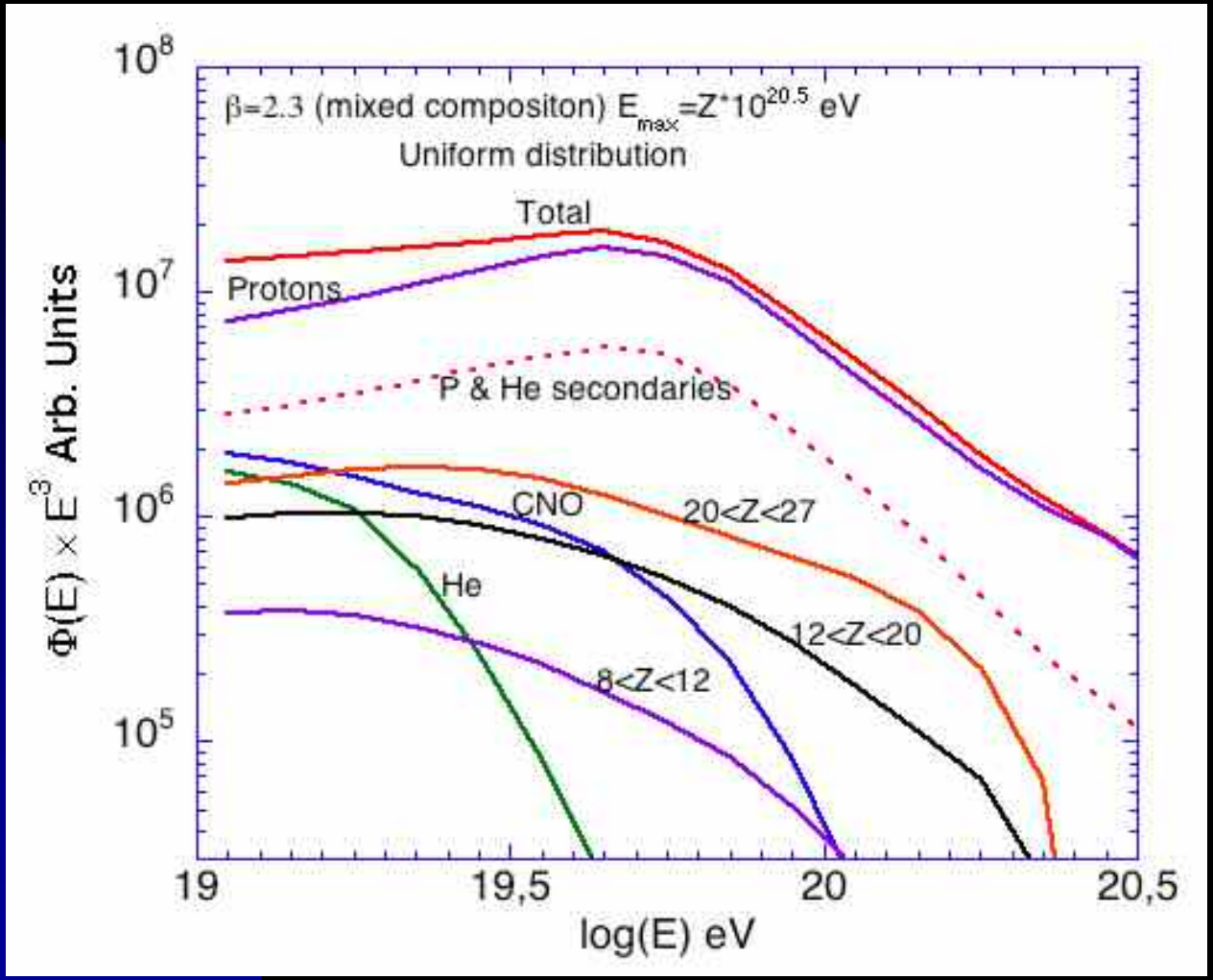
Allard

Fe Horizon



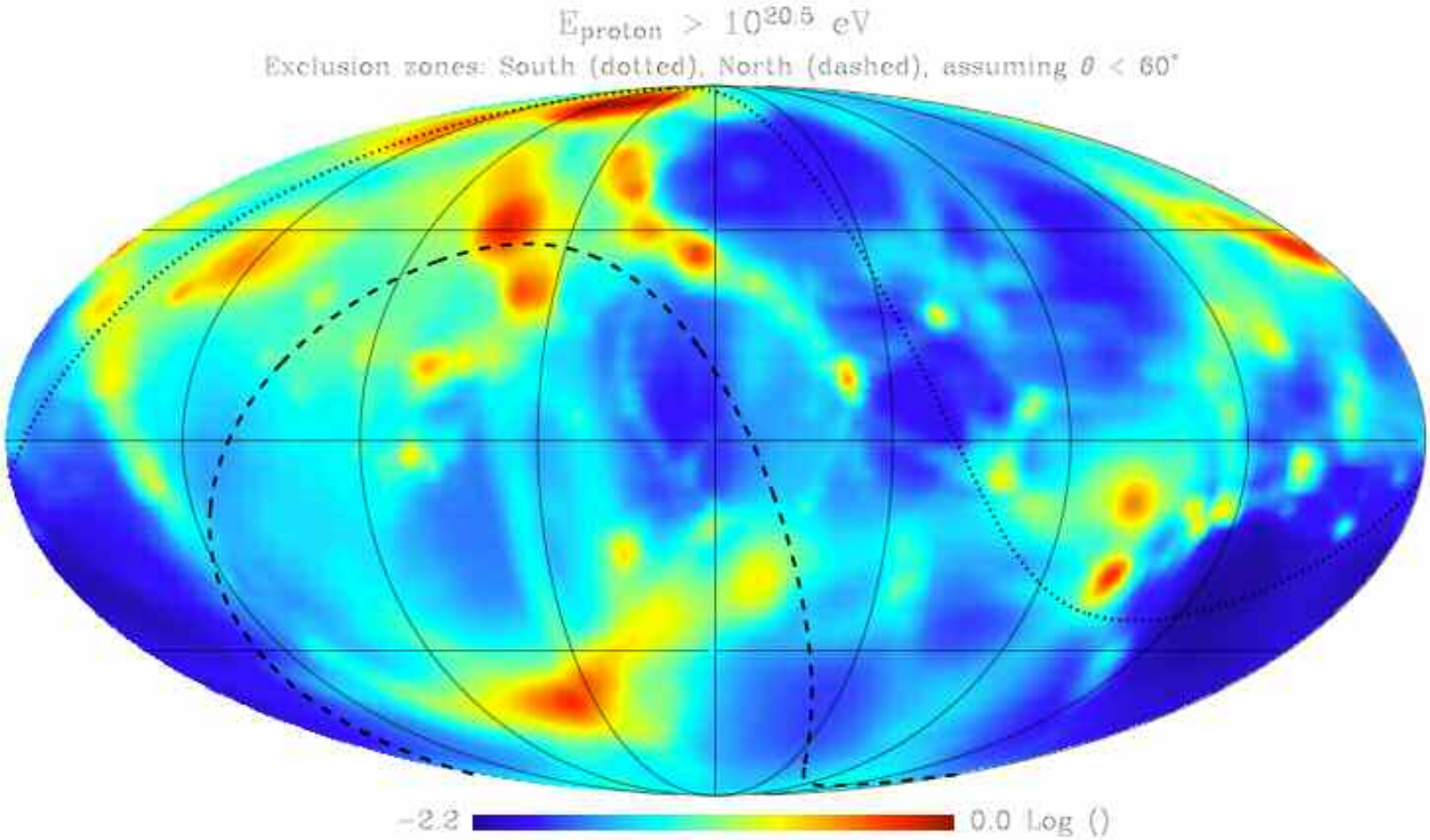
Allard

Observed Composition



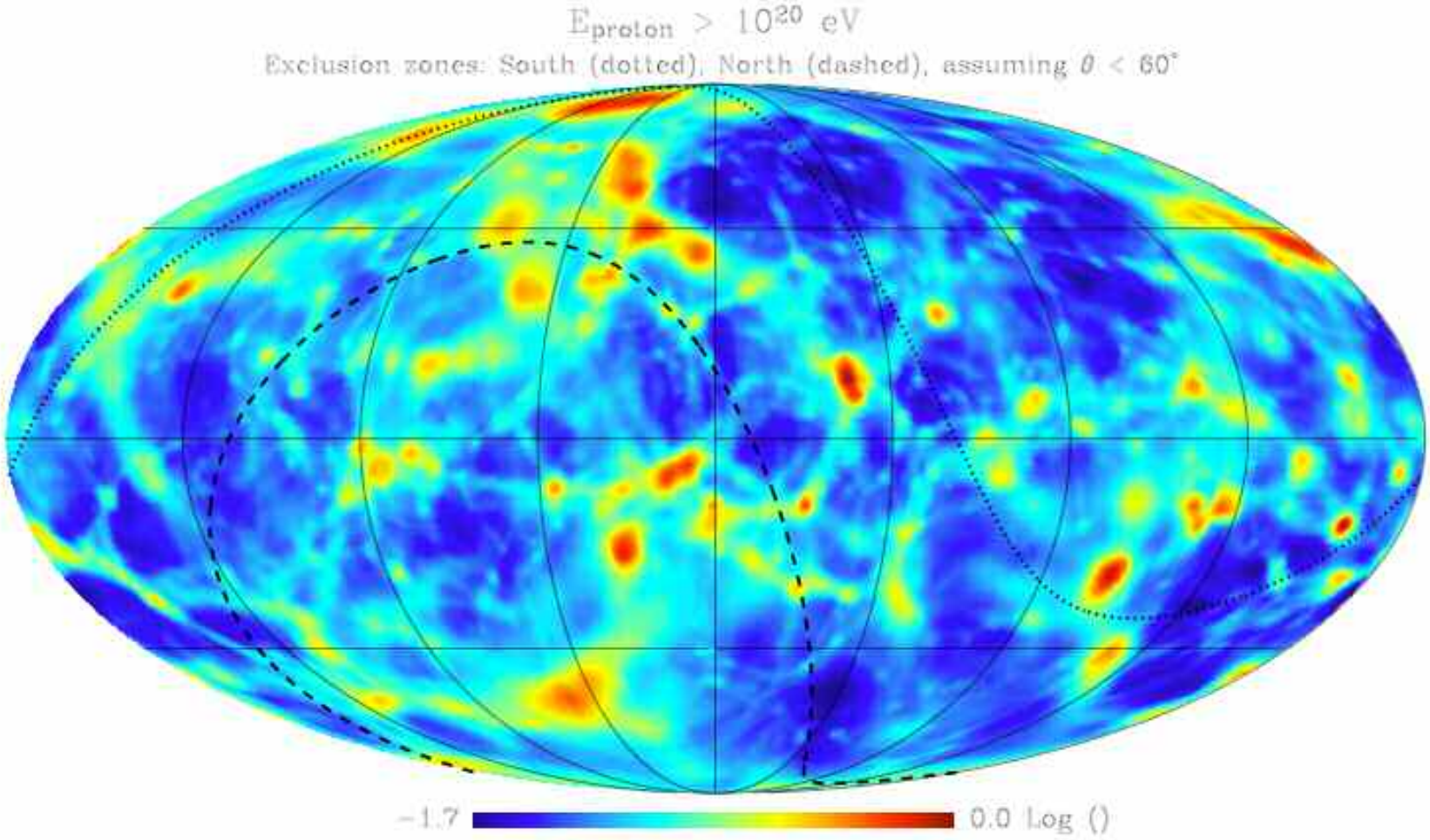
Allard

Protons with > $10^{20.5}$ eV



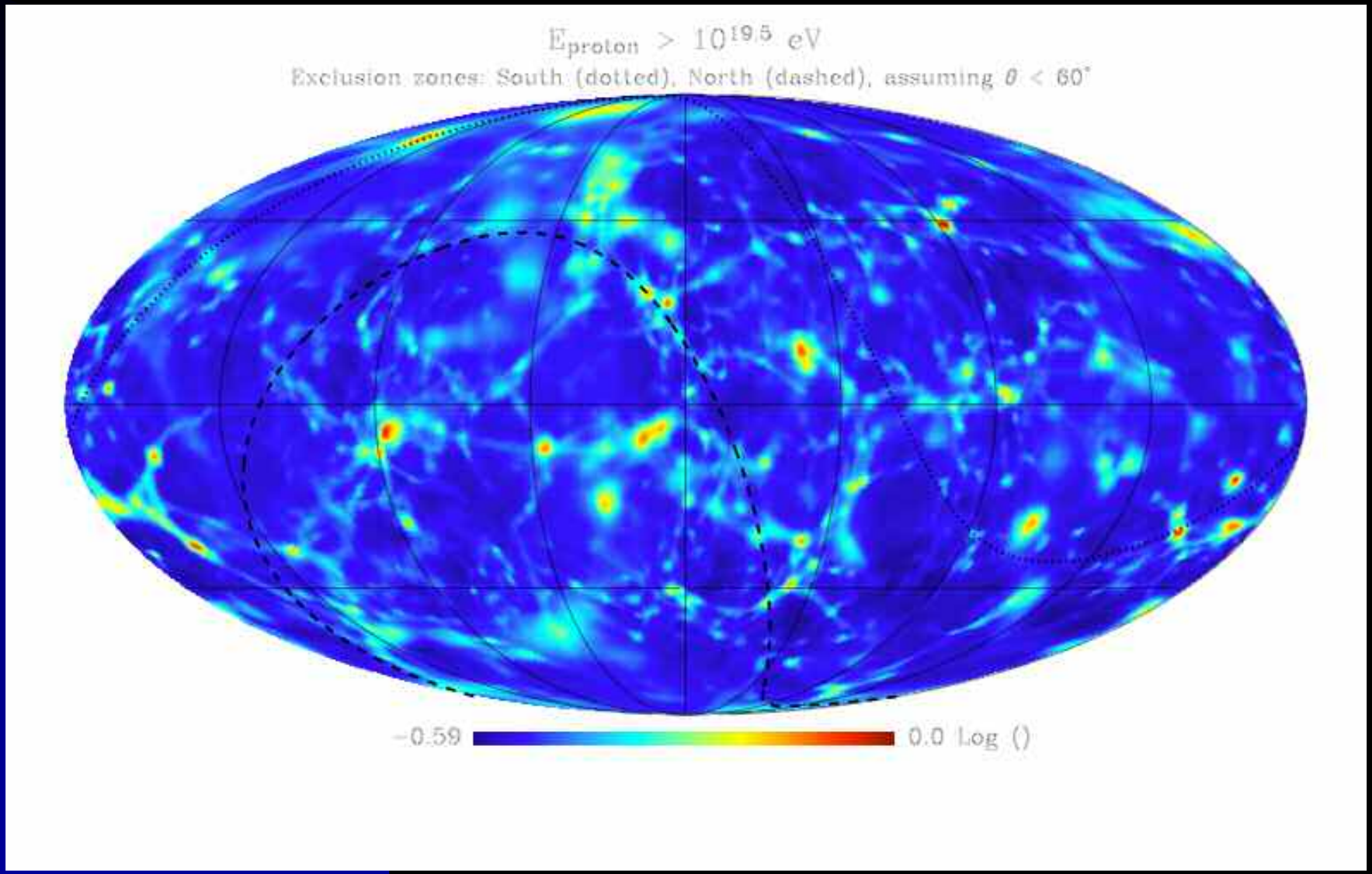
Armengaud

Protons with > 10^{20} eV



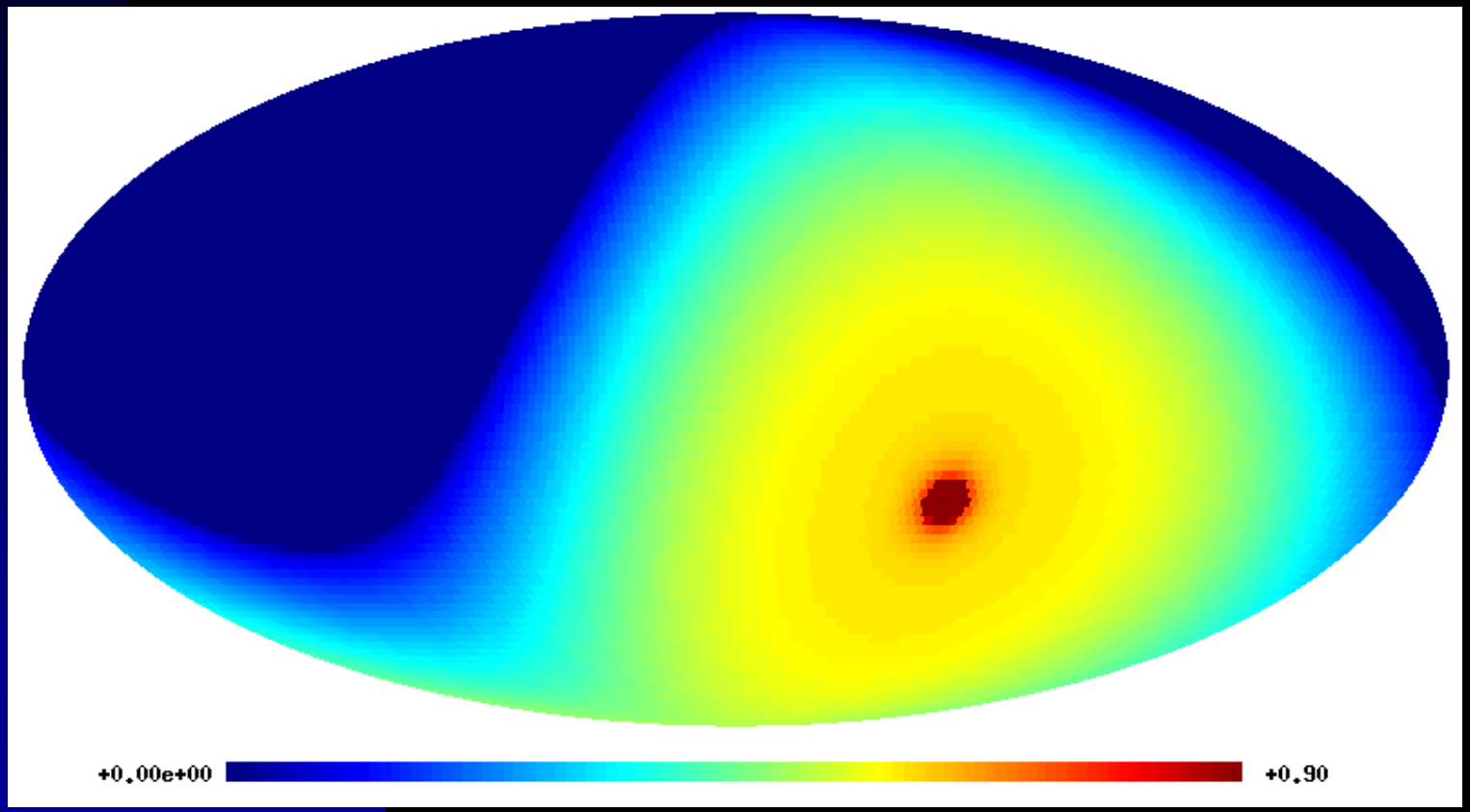
Armengaud

Protons with > $10^{19.5}$ eV



Armengaud

Sky @ Auger South = Exposure



Galactic Center in the Center!

Auger anisotropy results

Angular resolution of ~1°: good enough!

No large-scale signal (dipole) at any energy above 1 EeV

e.g. $\alpha < 0.7\%$ for $1\ \text{EeV} \leq E \leq 3\ \text{EeV}$

No significant emission from Galactic Center

No signal from BL-Lacs as possibly seen by HiRes

⟹ none of the previous reports has been confirmed…

Two prescriptions are being tested…

Stay tuned!

Remarks

1. Energy spectrum
   Mass composition
   Angular distribution and diffusion

   should be understood together

2. Multi- messengers - Neutrino and Photon limits
   Anisotropies - EGMF & GMF limits

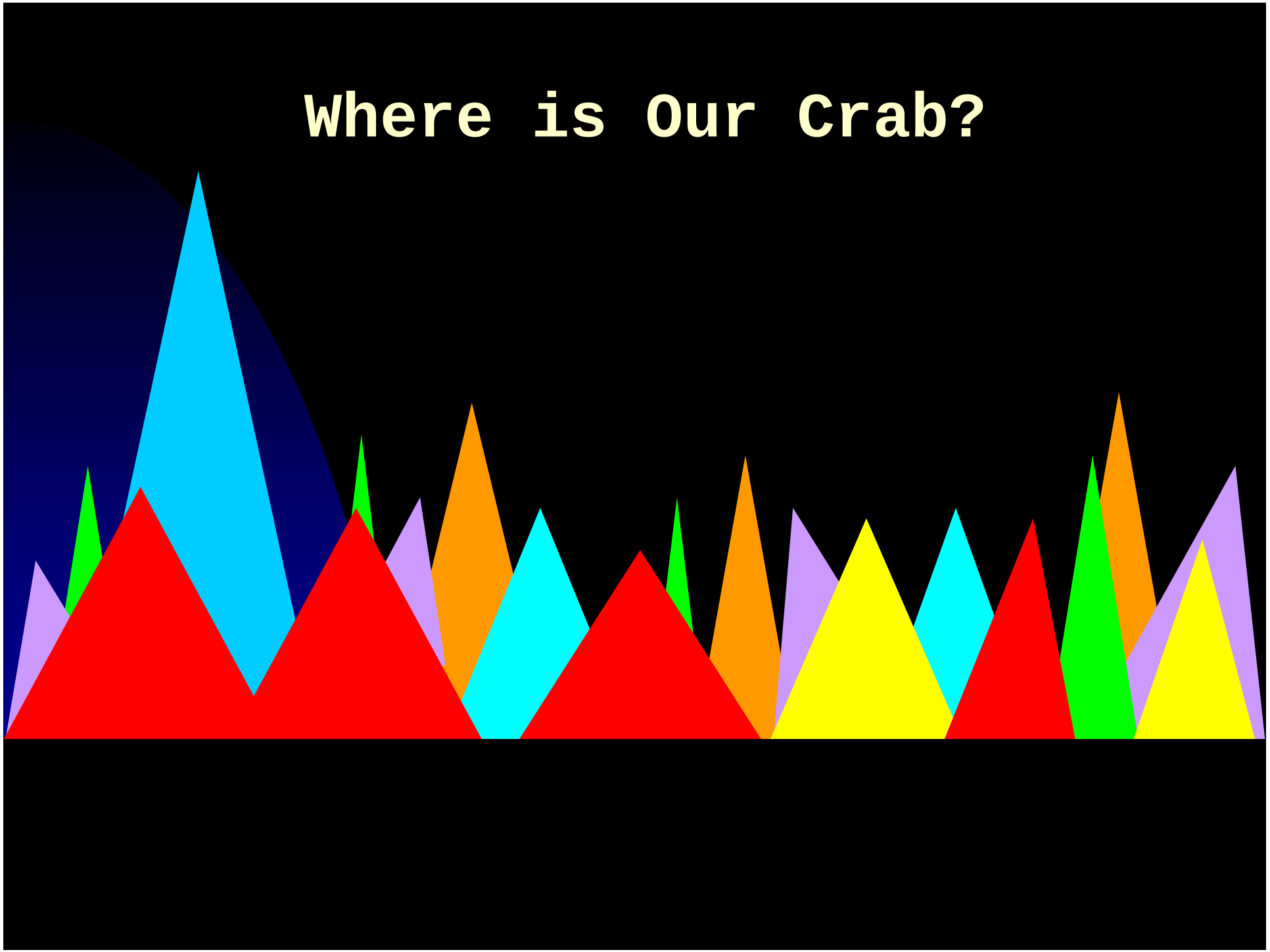
3. CR composition important: key to GCR/EGCR transition
   multi composition observables
   What is happening at Highest Energies???

   NB: Auger enhancements

4. Spectrum from $10^{18.05}$ to $10^{20.35}$ eV
   ($10^{18.45}$ to $10^{19.55}$ eV model indep anal)
   Ankle and Dip - GZK or E_{max}

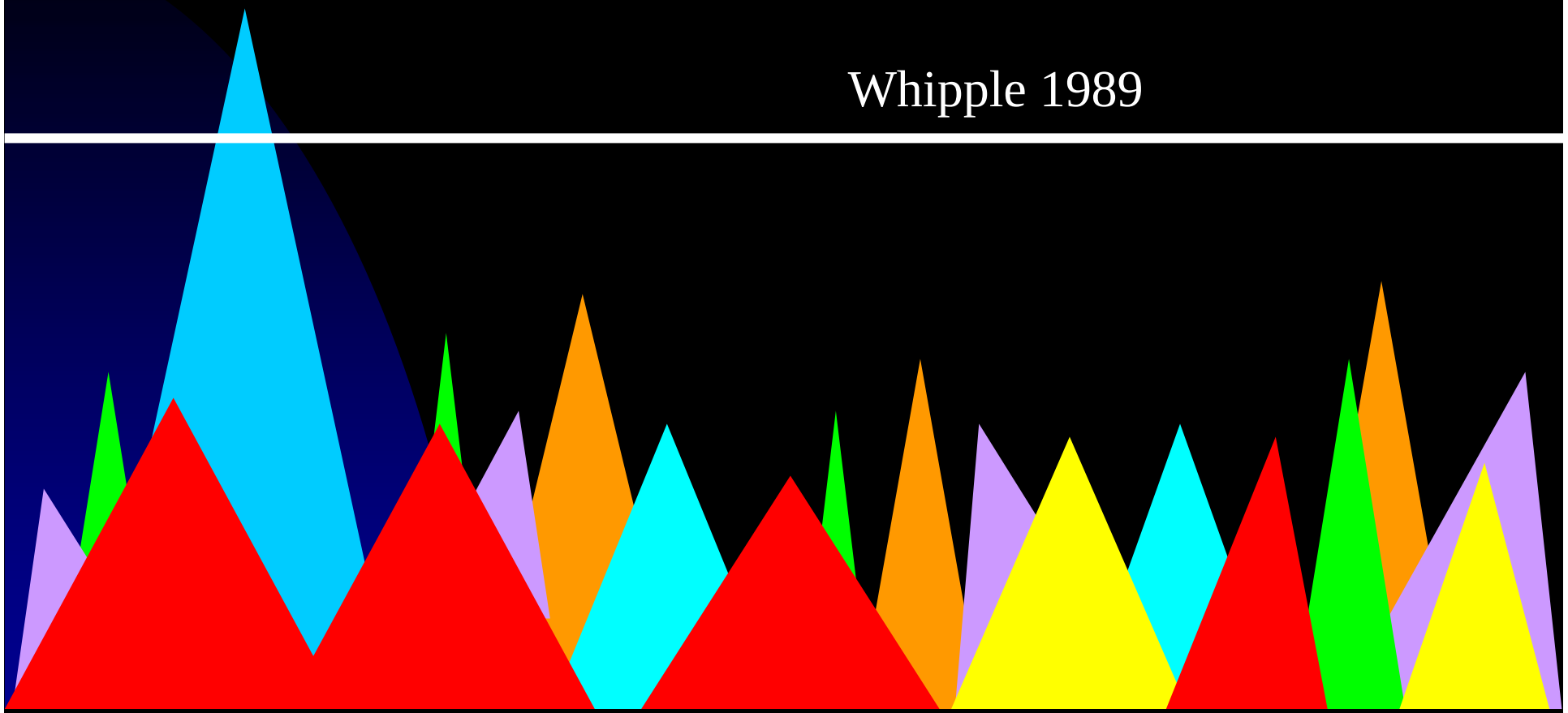
   GZK feature $\Rightarrow$ see nearby sources - Where is our Crab?

Where is Our Crab?



Where is Our Crab?

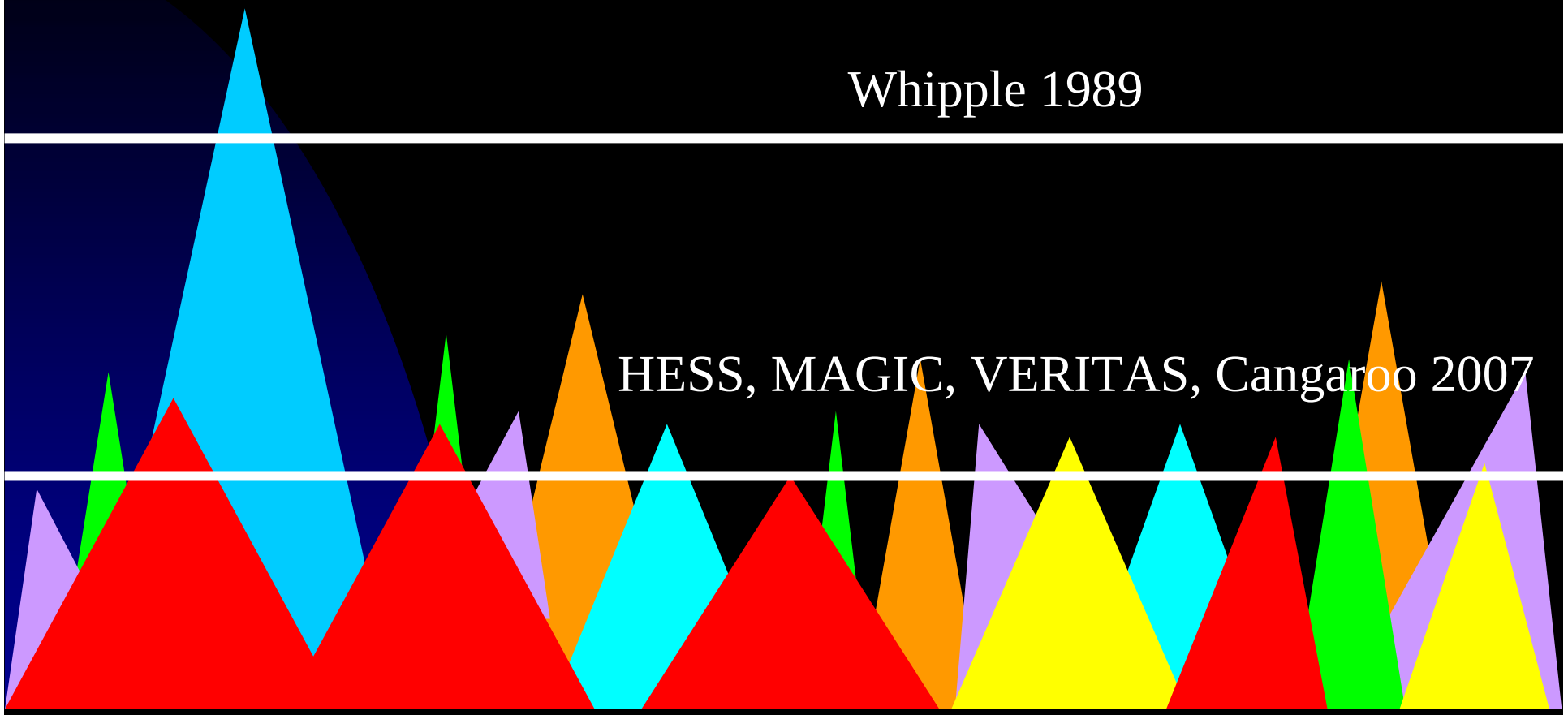
Whipple 1989



Where is Our Crab?

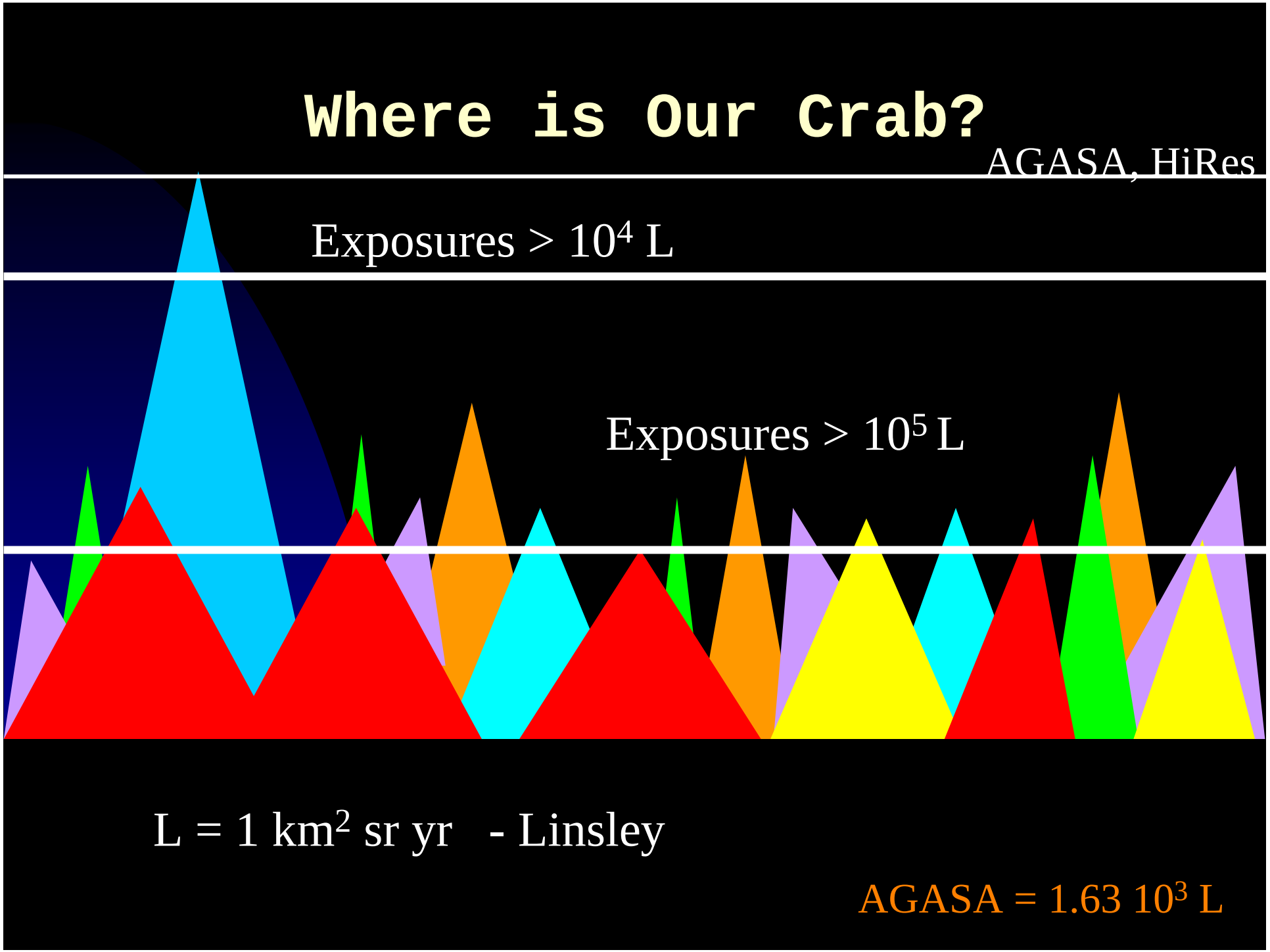
Whipple 1989

HESS, MAGIC, VERITAS, Cangaroo 2007



Where is Our Crab?

AGASA, HiRes



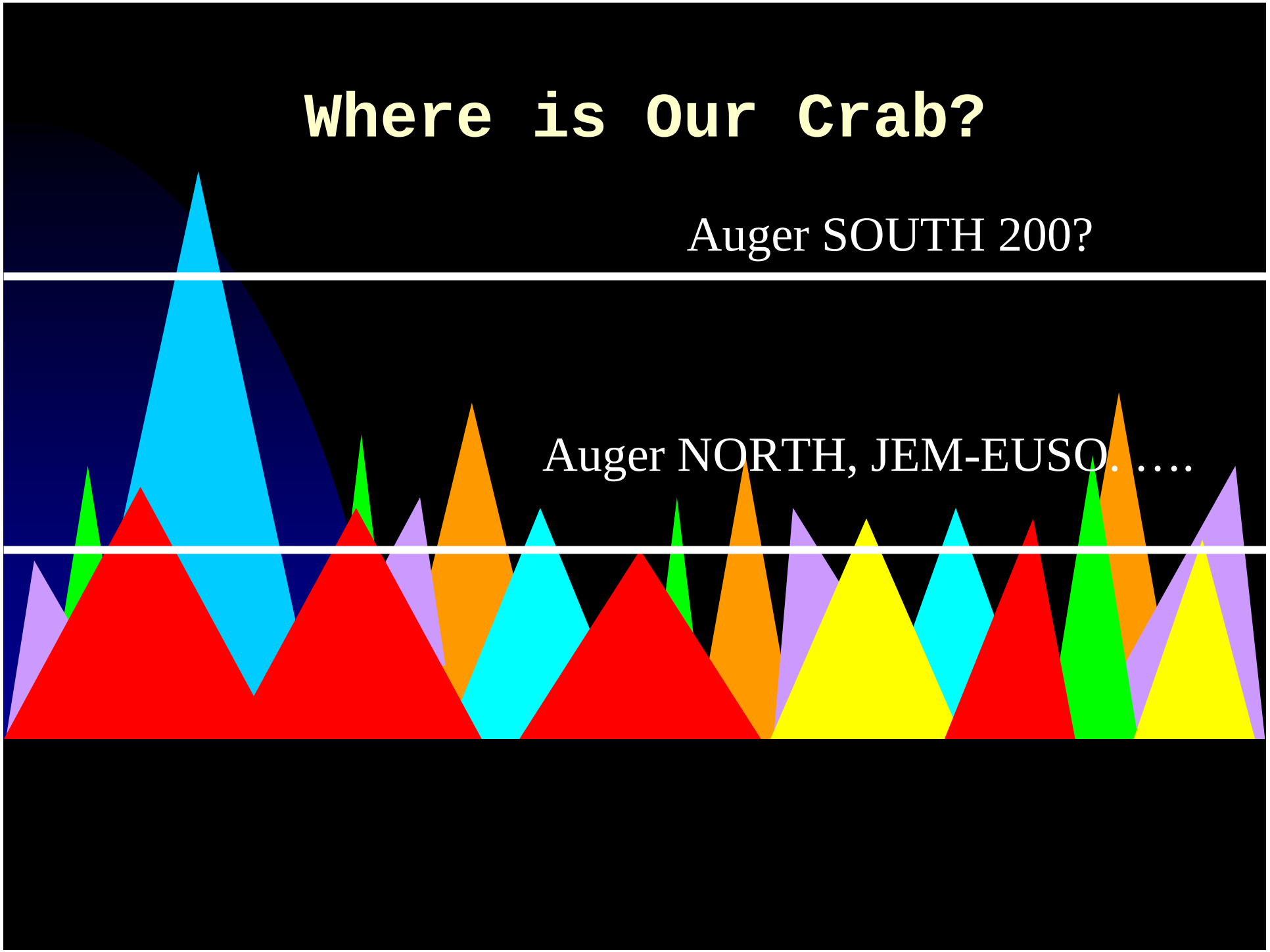
L = 1 km^2 sr yr - Linsley

AGASA = 1.63 10^3 L

Where is Our Crab?

Auger SOUTH 200?

Auger NORTH, JEM-EUSO. ….



All or Nothing

Auger SOUTH 20??

Auger SOUTH & NORTH

Auger SOUTH

3,000 km^2 = 1,157 mile^2

Hexagonal grid - 1.5 km separation

FD sites - 4 (180^o)

Auger NORTH

10,368 km^2 = 4,000 mile^2

SQUARE GRID - 1 mile separation

1 large PMT / tank

FD sites - 3 (180^o)

Baseline Timetable:

2008 site preparation (Engineering array)

2009 begin construction

2012 finish construction

20 yr lifetime

AS alone

2008: 10^4 L

2012: 5 10^4 L

2017: 10^5 L

2028: 2 10^5 L

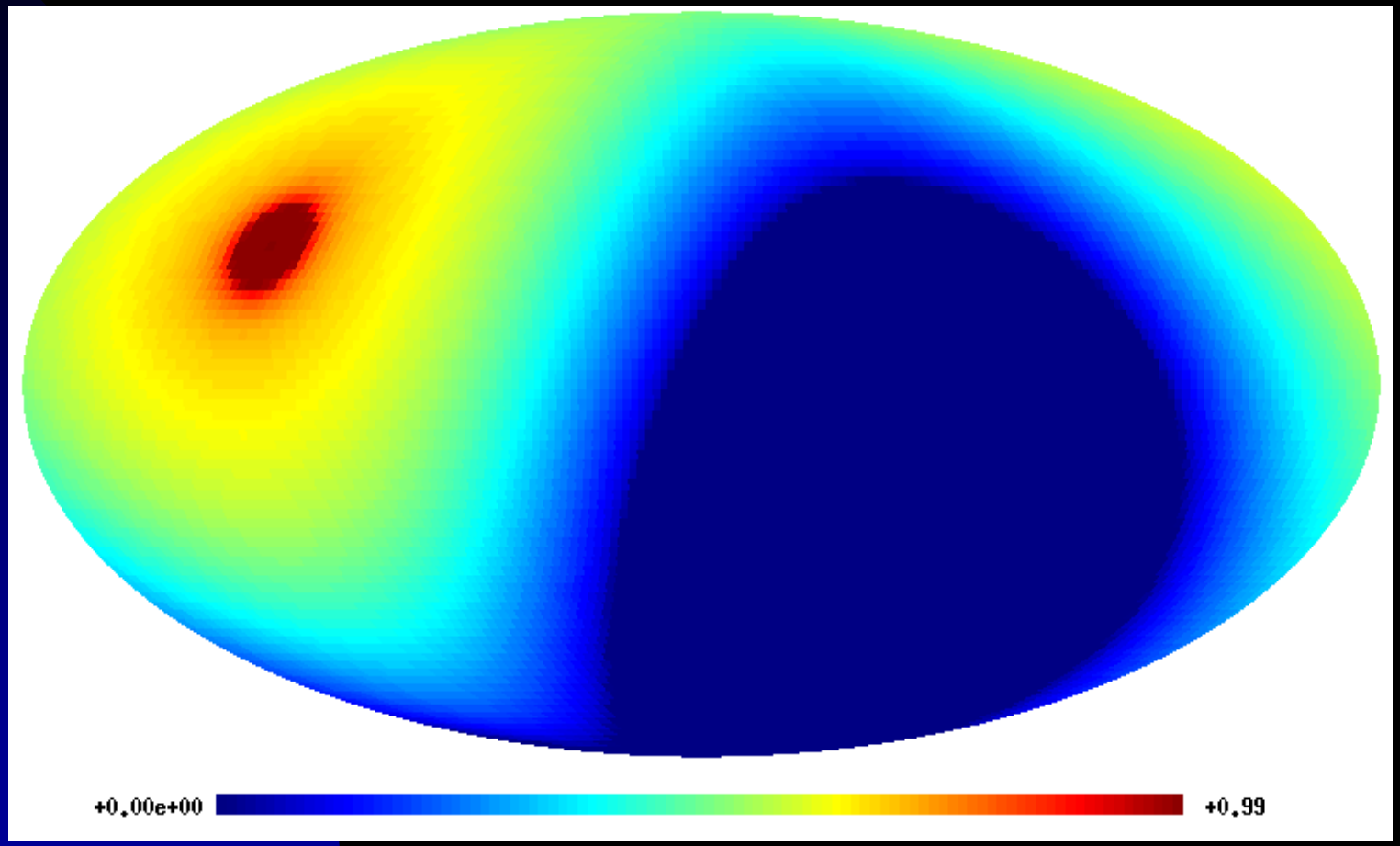
AN+AS

2011: 10^5 L

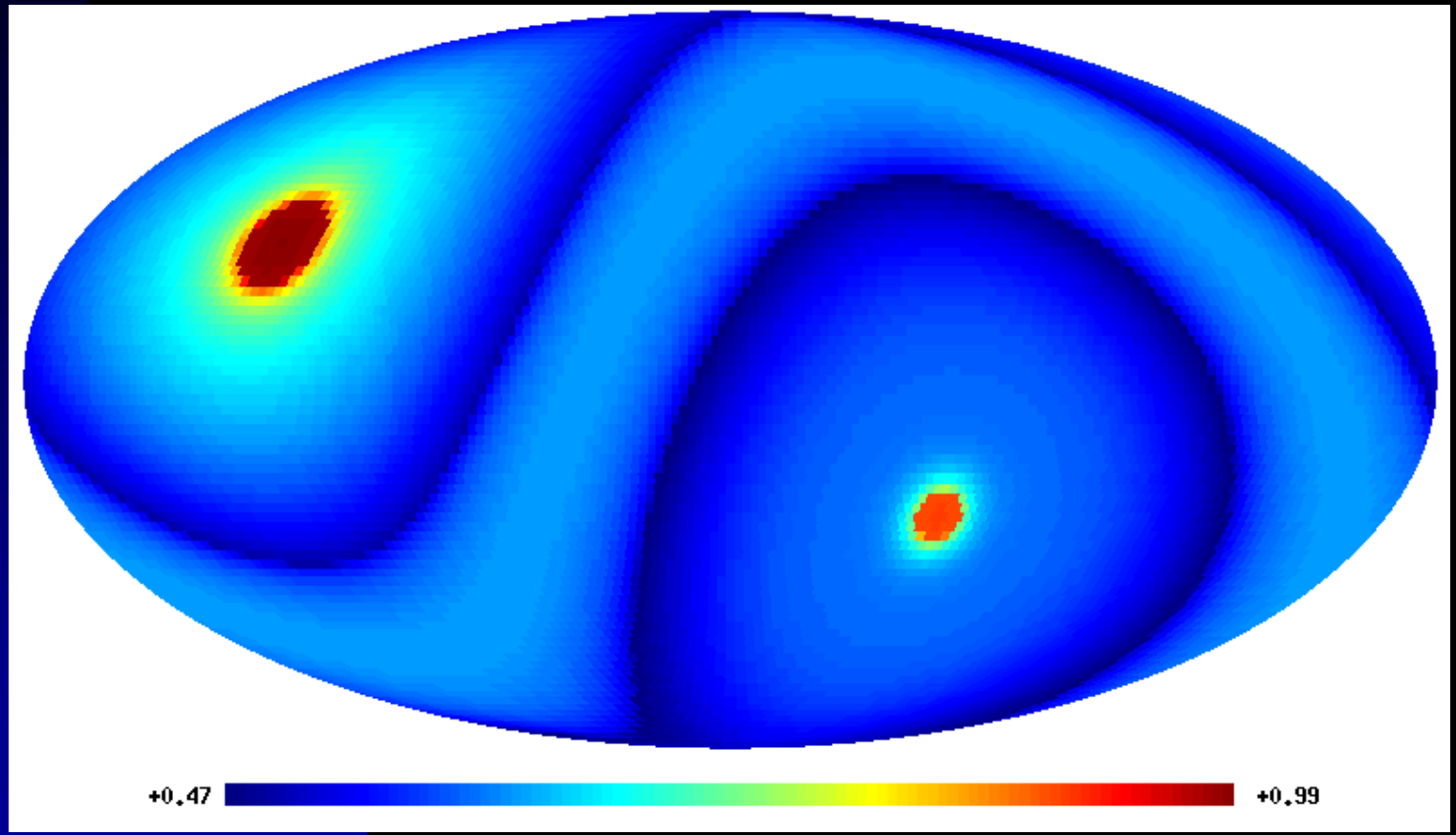
2021: 5 10^5 L

2032: 10^6 L

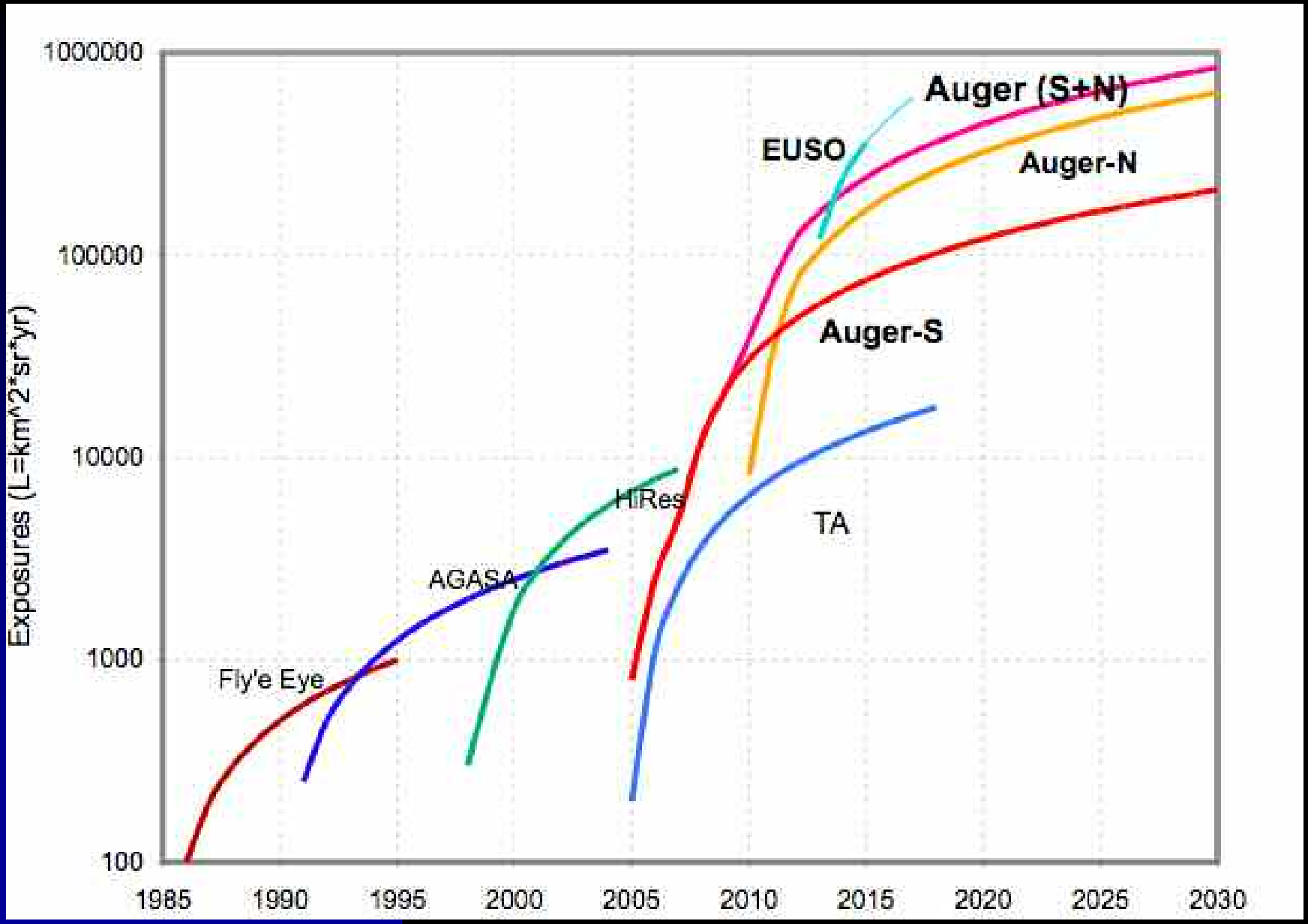
Sky Exposure Auger North

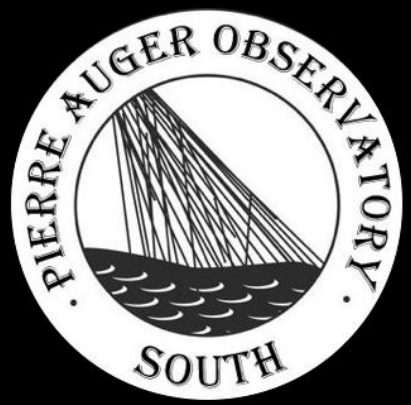


Sky Exposure
Auger North + South



Exposures (take vitamins!)





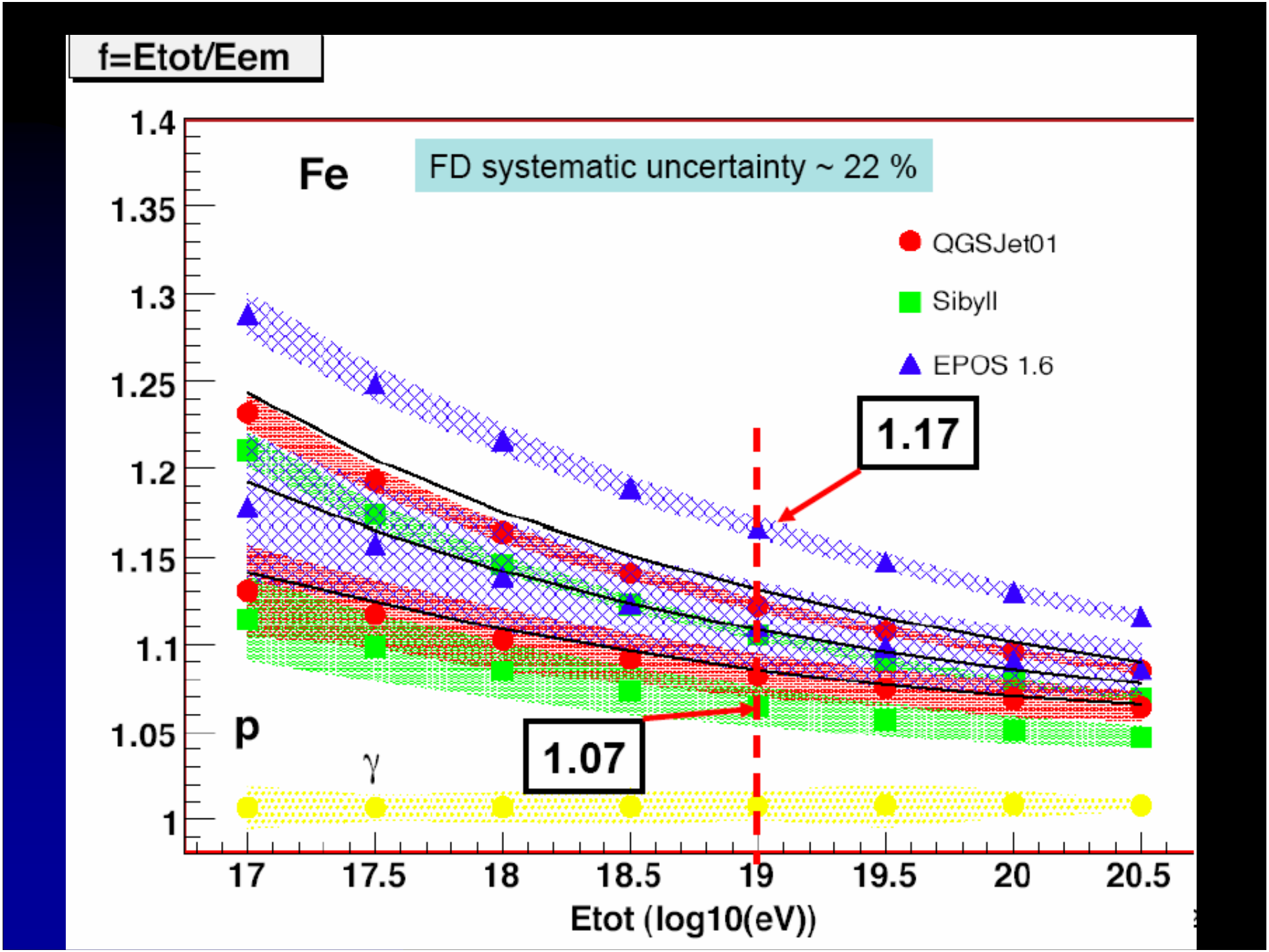
Pierre Auger Project South & North

to discover
Ultra-High Energy Cosmic Ray Sources
detect

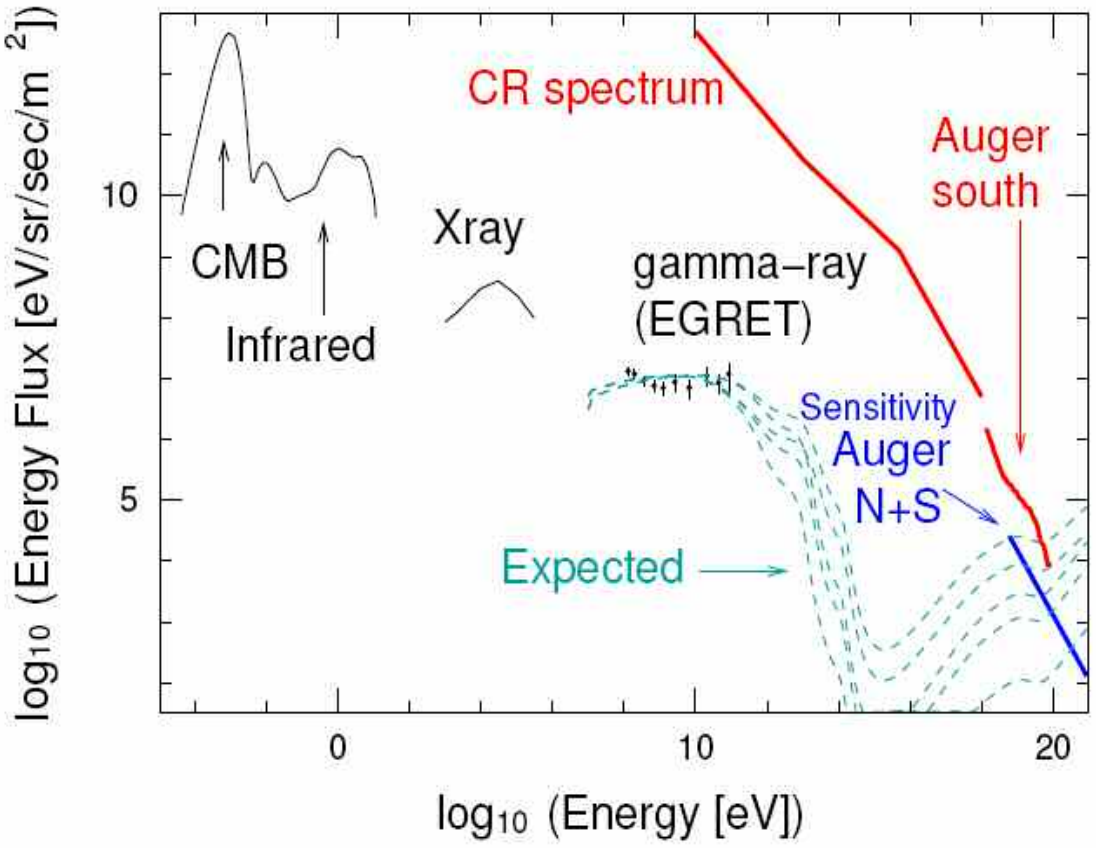
The Fun is just Beginning!

Charged Particle Astronomy

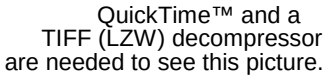
GRAZIE!!!


f=Etot/Eem
Fe
FD systematic uncertainty ~ 22 %
QGSJet01
Sibyll
EPOS 1.6
1.17
1.07
p
γ
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
17
17.5
18
18.5
19
19.5
20
20.5
Etot (log10(eV))

Intrinsic Multi-messenger capabilities



Neutrinos


QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.